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Refrigeration of COVID-19 Vaccines: Ideal Storage Characteristics, Energy Efficiency and Environmental Impacts of Various Vaccine Options

Alexandre F. Santos^{1,2}, Pedro D. Gaspar^{1,3}  and Heraldo J. L. de Souza^{2,*}

¹ Department of Electromechanical Engineering, University of Beira Interior, 6201-001 Covilhã, Portugal; d1682@ubi.pt (A.F.S.); dinis@ubi.pt (P.D.G.)

² FAPRO—Professional College, Curitiba 80230-040, Brazil

³ C-MAST—Centre for Mechanical and Aerospace Science and Technologies, 6201-001 Covilhã, Portugal

* Correspondence: heraldo@escolaprofissional.com.br; Tel.: +(55)-41-999748928

Abstract: This article considers the ideal storage conditions for multiple vaccine brands, such as Pfizer, Moderna, CoronaVac, Oxford–AstraZeneca, Janssen COVID-19 and Sputnik V. Refrigerant fluid options for each storage condition, thermal load to cool each type of vaccine and environmental impacts of refrigerants are compared. An energy simulation using the EUED (energy usage effectiveness design) index was developed. The Oxford–AstraZeneca, Janssen COVID-19 and CoronaVac vaccines show 9.34-times higher energy efficiency than Pfizer. In addition, a TEWI (total equivalent warming impact) simulation was developed that prioritizes direct environmental impacts and indirect in refrigeration. From this analysis, it is concluded that the cold storage of Oxford–AstraZeneca, Janssen COVID-19 and CoronaVac vaccines in Brazil generates 35-times less environmental impact than the Pfizer vaccine.

Keywords: SARS-CoV-2; vaccines; refrigeration; energy consumption; GWP; TEWI; EUED; environmental impact



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1. Introduction

Among the various controversial issues regarding SARS-CoV-2 are the questions of vaccine availability and logistics [1]. There are several different cold storage conditions between multiple brands. In the United States of America (USA) and Europe, the first approved vaccines were Pfizer–BioNTech and Moderna [2]. In Brazil, the first vaccines approved were CoronaVac and Oxford–AstraZeneca [3]. In Argentina, the first approved vaccine was Sputnik V. The Johnson & Johnson vaccine was the last vaccine to be approved both in the USA and Europe. It is a fact that the vaccine itself to be produced goes through several unique principles of refrigeration and clean rooms. One of the characteristics of these clean rooms is the BSL-03 (Biosafety Security Level) [4], with cascades of air pressure that are essential to ensure the safety of the users. After all the work to develop and produce the vaccines, however, they face cold storage and distribution issues. Thus, assessment of the electricity consumption and the environmental impacts helps each country to make the appropriate decision about which brand of vaccine to choose. In doing so, each must consider the operational costs and environmental factors produced during their cold storage [5].

According to Pfizer [6], the brand's vaccine needs a storage temperature of $-70\text{ °C} \pm 10\text{ °C}$. As soon as a vaccination center receives a thermal sender with Pfizer's vaccines, it has three storage options:

- Ultra-low-temperature freezers, which are available on the market and can extend service life by up to six months;

- Pfizer thermal shipper, in which doses will arrive, which can be used as temporary storage units, recharging with dry ice every five days for up to 30 days of storage;
- Refrigeration units commonly available in hospitals. The vaccine can be stored for five days, refrigerated at 2–8 °C.

After storage for up to 30 days in Pfizer’s thermal shipper, vaccination centers can transfer the vials to 2–8 °C storage conditions for an additional five days, for a total of up to 35 days. Once defrosted and stored under 2–8 °C conditions, the bottles cannot be refrozen or stored under freezing conditions.

The various storage options for vaccination centers allow equitable access to Pfizer’s vaccine in areas with different infrastructure.

According to the Centers for Disease Control and Prevention (CDC) of the USA, the characteristics of the Moderna vaccine storage are [7]:

- The vaccine will arrive frozen between −25 °C and −15 °C and needs to be stored at the same temperature. After defrosting, the vaccine may be thawed in the refrigerator or at room temperature [8];
- Refrigerator: 2 °C to 8 °C for 2 h and 30 min;
- Room temperature: between 15 °C and 25 °C for 1 h.;
- Unpunctured vials may be kept between 8 °C and 25 °C for up to 12 h;
- Thawed vaccines cannot be refrozen;
- Vaccine vials may be stored in the refrigerator between 2 °C and 8 °C for up to 30 days before vials are punctured. After 30 days, any remaining vials should be removed from the refrigerator and discarded following manufacturer and jurisdiction guidance on proper disposal [7].

Zeng [9] stated that the CoronaVac vaccine can be stored at normal refrigerator temperatures—that is, 2 °C to 8 °C—and it remains valid for a period of up to three years, offering an advantage for distribution in places where access to refrigeration is a challenge.

The British government’s instructions regarding the Oxford–AstraZeneca vaccine are [10]:

- It can be stored in a refrigerator (2 °C to 8 °C);
- It should not freeze;
- After the first dose is withdrawn, the vaccine should be used as soon as possible and within six hours. During use, it can be stored from 2 °C to 25 °C.

The Sputnik V vaccine has a physical robustness that allows storage at temperatures near −18 °C, which is feasible for many supply chains [11].

According to the CDC of the USA, the storage temperature of the Janssen COVID-19 vaccine produced by Johnson & Johnson is between 2 °C and 8 °C [12].

The lower-limit storage conditions of the different SARS-CoV-2 vaccines are shown in Table 1, since these will be the values used for further calculations.

Table 1. Vaccine storage temperatures.

Vaccine	Storage Temperature °C
Pfizer–BioNTech	−70
Moderna	−25
CoronaVac	2
Oxford–AstraZeneca	2
Sputnik V	−18
Janssen COVID-19	2

Knowing the importance of electric energy and the environmental impacts that cold storage can generate, this paper aims to address the following research questions: (1) How can the environmental impact of cold storage be measured? (2) Which refrigerant gases are commonly used for these temperatures? (3) What suggestions can be made regarding

the reduction of environmental impacts, since, with the growth of new types of viruses, vaccines will become more frequent?

2. Materials and Methods

A comparison of the energy consumption of vaccine cold storage systems requires the determination of their cooling load. For example, equipment at standard capacity for 100,000 doses has the following characteristics [13]:

- Height, $H = 2050$ mm;
- Length, $L = 1600$ mm;
- Width, $W = 790$ mm;
- Gross volume, $V_g = 2.59$ m³;
- Useful volume, $V_u = 1.05$ m³;
- Estimated dose capacity, $n = 100,000$;
- Dose Volume, $V_d = 0.3$ ml ($= 3.0 \times 10^{-7}$ m³).

The equipment walls have a minimum thermal insulation panel depth of 70 mm, comprising thermal insulation panels with expanded injected polyurethane free of CFC (chlorofluorocarbons). The front doors are glassed. The Coolpack software was used to determine the cooling load using the cold storage temperatures in Table 1 with an ambient temperature of 24 °C. The results of the cooling load are shown in Table 2 [14]. It is important to point out that cold room temperatures were used for the doses entering the refrigeration equipment. Additionally, the inlet vaccine temperatures (see Table 1) lead to multiple air changes in 24 h; with an air change factor, ACF = 43.5.

Table 2. Vaccine thermal loads.

Vaccine	Inlet Vaccine Temperature (°C)	Cold Room Temperature (°C)	Cooling Load (Kw)
Pfizer–BioNTech	−60	−70	2.23
Moderna	−15	−25	1.38
CoronaVac	8	2	1.02
Oxford–AstraZeneca	8	2	1.02
Sputnik V	−12	−18	1.28
Janssen COVID-19	8	2	1.02

The coefficient of performance (COP), the ratio of cooling provided to electric energy consumption, is the most common parameter for comparing the performance of refrigeration equipment. Specifically, ASHRAE 90.1-2019 (Energy Standard for Buildings Except Low-Rise Residential Buildings) [15] dictates the energy efficiency parameters. There are some parameters for commercial refrigerators, commercial freezers and refrigeration. The specific energy consumption given in kWh/day is based on the AHRI 1201-2013 standard. However, this AHRI standard does not specify a range for vaccine equipment. Thus, one of the goals of this study is to create a method to compare this type of equipment, the Vaccine EUED (energy usage effectiveness design), and to compare the greenhouse effect to Vaccine TEWI (Total Equivalent Warming Impact) [16]. To compare the energy efficiency of cold vaccine storage equipment, it is necessary to gauge some parameters, such as differentiating between air intake and condensation temperature, and differentiating between storage temperature and evaporation temperature. In addition to the isentropic coefficient of the compressor, the AHRI 210/240-2017 [17] normally uses the difference between the air inlet and condensation temperatures of 10 °C, due to the vaccine refrigerators being located in acclimatized places. The ANSI/ASHRAE Standard 72-2018 considers that the intake of air in the condenser must be 24 °C at room temperature [18]. Table 3 includes the temperature values and parameters for each type of vaccine.

Table 3. Vaccines and equipment characteristics.

Vaccine	Inlet Condenser Temperature (°C)	RFCT (°C)	Cold Room Temperature (°C)	RFET (°C)	EFISEN
Pfizer–BioNTech	24	34	−70	−80	0.7
Moderna	24	34	−25	−35	0.7
CoronaVac	24	34	2	−8	0.7
Oxford–AstraZeneca	24	34	2	−8	0.7
Sputnik V	24	34	−18	−28	0.7
Janssen COVID-19	24	34	2	−8	0.7

Note: RFCT = Refrigerant fluid condensation temperature. RFET = Refrigerant fluid evaporation temperature. EFISEN = Isentropic efficiency.

After determining the parameters for measuring the COP, it is important to choose the refrigerant considering (1) the Montreal protocol encouraging the use of zero ozone depletion potential (ODP) refrigerants, disregarding the phasing out of refrigerants such as R-12 and R-502 [19]; and (2) the Kigali protocol [20] encouraging the use of refrigerants with low Global Warming Potential (GWP). For example, the R-404A has a high GWP index (GWP = 3922), while R-134A has a GWP = 1430. Although natural fluids have low GWP, they are not used in vaccine refrigerators. For example, an ammonia system is very complex for small systems, besides its dangerous toxicity [21].

The guideline for establishing or improving primary and intermediate vaccine stores set by the World Health Organization (WHO) [22] states that R134A is often used for +4 °C cold rooms but is not suitable for −20 °C freezer rooms. Various alternative gases are available for this purpose, among them the gas R404A. However, it is already being phased out (virgin R404A can no longer be used in new equipment, but recovered or reclaimed R404A can be used until the end of 2030) and superseded by new, low-GWP refrigerants such as R454C, R455A and R1234yf for small packaged equipment and medium-sized multi-compressor equipment, although it is still used in a number of systems.

The most used refrigerants were prioritized, specifically those with medium evaporation temperatures. Thus, the refrigerant used in the refrigeration systems of the CoronaVac, Oxford–AstraZeneca and Janssen COVID-19 vaccines is the R-134A. The refrigerant R-449A (low GWP compared to R-404A) is used in the refrigeration system of Moderna and Sputnik V. For the Pfizer–BioNTech vaccine, the refrigerant R-508B, with special refrigerant and ultra-low evaporation temperature applications associated with the R-449A, is used. Although studies have already predicted the use of low-GWP refrigerants such as the R-449A, in practice, in Brazil, R-404A is still widely used. As a result, a simulation with both options will be developed. Table 4 shows the refrigerant selected for the refrigeration system of each vaccine due to thermal requirements. The table also shows the GWP, the refrigerant load required, the equivalent CO₂ emissions and the CO₂ emissions when R-404A is used instead of low-GWP R-449A.

Table 4. Vaccines and GWP.

Vaccine	Refrigerant	GWP	Refrigerant Load (kg)	CO ₂ Emissions (R 449A) (kg)	CO ₂ Emissions (R 404A) (kg)
Pfizer–BioNTech	R-508B & R-449A	13,396 & 1430	0.15 + 0.45	2652.90	3774.30
Moderna	R-449A	1397	0.405	565.78	1588.41
CoronaVac	R-134A	1430	0.27	386.10	386.10
Oxford–AstraZeneca	R-134A	1430	0.27	386.10	386.10
Sputnik V	R-449A	1397	0.37	516.89	1451.14
Janssen COVID-19	R-134A	1430	0.27	386.10	386.10

The refrigerant loads were simulated in FAPRO Laboratories in Curitiba-Paraná, Brazil. Figure 1 shows the differences between the environmental impact in terms of CO₂ emissions, assuming the use of R-404A initial refrigerant load. Despite the heat load for the Pfizer–BioNTech vaccine, it is 2.2-times greater than that of Oxford–AstraZeneca, CoronaVac and Janssen COVID-19 (see Table 2). The environmental impact due to the

refrigerant, which is required to comply with the needed storage temperature, has a difference of almost 10 times.

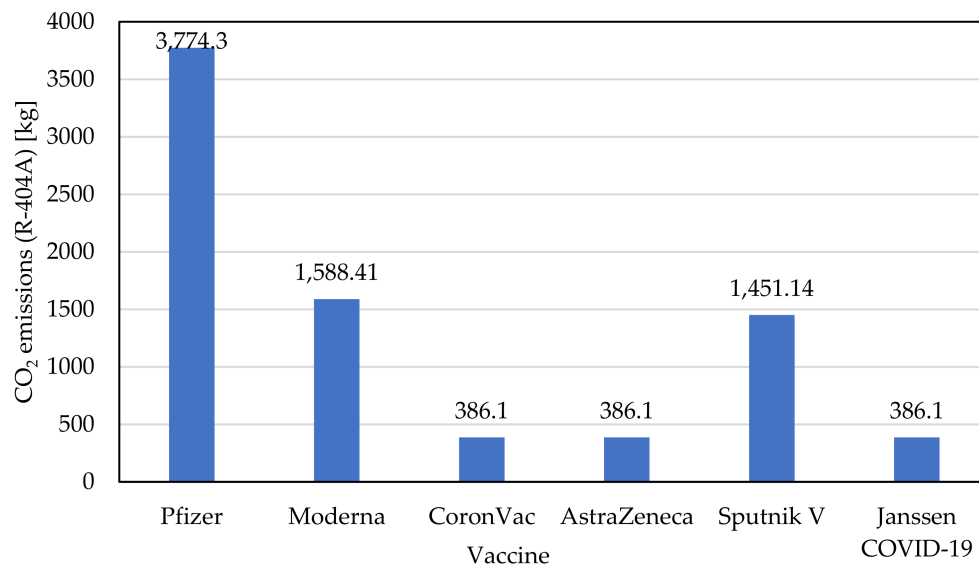


Figure 1. Environmental impact in terms of CO₂ emissions, assuming the use of R-404A initial refrigerant load.

With the thermal requirements and refrigerants chosen, the next step is the measurement of the COP. Ultra-low-temperature refrigerators require special refrigerants. The refrigerant R-508B is used in this simulation. The Chemours software, Expert 1.0, was used for this simulation [23]. Figure 2 shows the COP of the refrigeration system with condenser fans and an evaporator for vaccines.

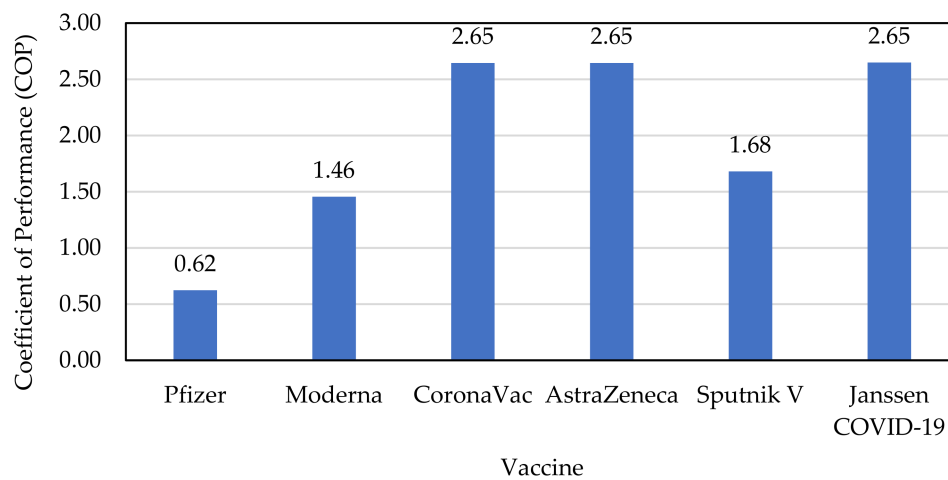


Figure 2. COP of refrigeration system with condenser fans and evaporator for vaccines.

2.1. Vaccine Energy Usage Effectiveness Design (EUED)

The energy usage effectiveness design (EUED) index was initially proposed to measure the energy efficiency in datacenters (DC) [24–29].

The EUED index provides a more comprehensive and global view of the energy consumption as it emphasizes the environment [30–32]. This analysis provided by the index involves all natural parameters of a region, considering the location where a DC is to be installed (air dry and wet bulb temperatures, air dew point temperature and soil

temperature). The EUED given by Equation (1) can be used in the design phase to predict a measurement of the DC efficiency.

$$\text{EUED} = \frac{\text{Total energy with entalpic variations [kWh/yr]}}{\text{Specific consumed energy by equipment [kWh/yr]}} \quad (1)$$

The EUED index uses the climatic data of 8760 h per year. It stipulates psychrometric conditions for the use of free cooling, evaporative systems and variable COPs. This index is adapted for vaccine refrigerators. It is important to note that these refrigerators are usually located in climatized facilities, so a constant condensation temperature was used. Some operational particularities were determined during the tests developed in the FAPRO laboratory. First, the price of R-508B is extremely high and it is not available in refrigeration stores in Brazil. Second, there is extreme risk associated with working at ultra-low-temperatures and this required the use of special protective clothing to avoid work accidents. Additionally, the experimental tests determined that the compressor was used 60% of the time. This value arose when the cooling loads of the vaccines from the minimum to the maximum limits were considered. For example, for a CoronaVac, Oxford–AstraZeneca and Janssen COVID-19 vaccine being stored at +8 °C, and maintained at +2 °C, after thermal equilibrium, the thermal load is only given by thermal conduction and infiltration. The Vaccine EUED is defined by Equation (2):

$$\text{Vaccine EUED} = \left(\frac{\text{Thermal Load [kW]}}{\text{COP}_{\text{complete}} \left[\frac{\text{kW}}{\text{kW}} \right]} \right) \cdot \text{Load Factor (\%)} \cdot 8760 \text{ hours} \quad (2)$$

Considering the thermal load values shown in Table 2, the COP determined and shown in Figure 2, a compressor load factor of 0.6 and 8760 h of operation, the Vaccine EUED index, representing the energy consumption for each vaccine refrigeration system during a year, is shown in Figure 3.

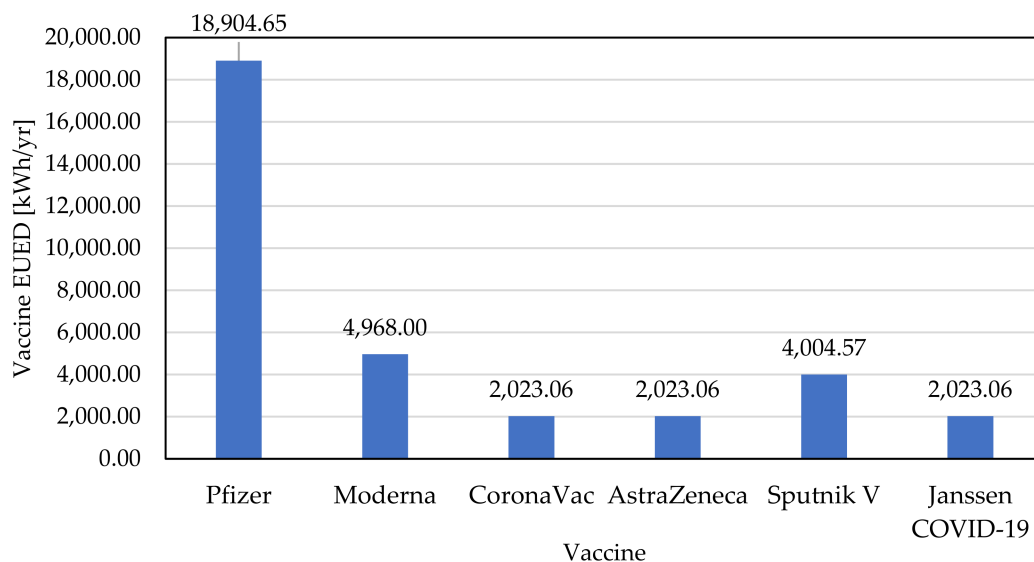


Figure 3. Vaccine Energy Usage Effectiveness Design (EUED) index.

It is important to note that the difference between vaccines is substantial. For example, the refrigeration system for a vaccine from Pfizer–BioNTech consumes nine-times more energy than the system for a vaccine from Oxford–AstraZeneca, CoronaVac or Janssen COVID-19.

2.2. Vaccine Total Equivalent Warming Impact (TEWI)

Total equivalent warming impact (TEWI) is a metric of the global warming impact of equipment based on the total emissions related to the global warming impact (GWP) during the operation of the equipment and the removal of operational fluids at the end of life. TEWI takes into account both direct and indirect emissions [33]:

- Direct emission—refrigerant released during the lifetime of the equipment, including losses not recovered on the final disposal;
- Indirect emission—the impact of CO₂ emissions from fossil fuels used to generate the electric energy that is used in the operation of the equipment throughout its lifetime.

The method of calculating TEWI is given by Equations (3) and (4):

$$\text{TEWI} = \text{GWP}(\text{direct, refrigerant leaks including EOL}) + \text{GWP}(\text{indirect, operation}) \quad (3)$$

$$\text{TEWI} = (\text{GWP} \cdot L_{\text{annual}} \cdot n) + \text{GWP} \cdot m \cdot (1 - \alpha_{\text{recovery}}) + (E_{\text{annual}} \cdot \beta \cdot n) \quad (4)$$

where:

EOL = end of life;

GWP = global warming potential of refrigerant, rel. to CO₂ (GWP CO₂ = 1);

L_{annual} = leakage rate p.a. (kg);

n = system operating life (yrs);

m = refrigerant charge (kg);

α_{recovery} = recovery/recycling factor from 0 to 1;

E_{annual} = energy consumption per year (kWh p.a.);

β = indirect emission factor (kg CO₂/kWh) [9].

The results point out that refrigerant fluids have proportionally a greater impact in Brazil than in other important world markets.

The indirect emission factor, β , given in kg CO₂/kWh, varies according to the energy matrix. For example, in Brazil, the matrix of the energy system is shared in the same transmission for the whole country. According to National Energy Balance Brazil (BEN), Brazil emits 0.088 kg CO₂/kWh [34]. According to the Energy Information Administration (EIA) [35], the United States of America emits 0.417 kg CO₂/kWh. The Vaccine TEWI index uses TEWI concepts in addition to the Vaccine EUED index, for a 10-year lifecycle, is given by Equation (5) [36]:

$$\text{Vaccine TEWI} = \text{GWP}(\text{direct leaks including EOL}) + (\text{yearly EUED} \cdot \beta \cdot 10) \quad (5)$$

The results for the Vaccine TEWI of the refrigeration systems for storing some types of COVID-19 vaccines in Brazil and in the USA are shown in Table 5 applying Equation (5).

Table 5. Direct and indirect TEWI of each vaccine refrigeration system for Brazil and the USA.

Vaccine	Refrigerant	TEWI (Direct)	EUED (kWh/yr)	TEWI (Ind. USA)	TEWI (Ind. USA)	TEWI (Total Brazil)	TEWI (Total USA)
Pfizer–BioNTech	R-508B & R-449A	4111.99	18,904.65	16,636.09	78,832.39	20,748.09	82,944.39
Moderna	R-449A	876.97	4968.00	4371.84	20,716.56	5248.81	21,593.53
CoronaVac	R-134A	598.45	2023.06	1780.29	8436.16	2378.75	9034.62
Oxford–AstraZeneca	R-134A	598.45	2023.06	1780.29	8436.16	2378.75	9034.62
Sputnik V	R-449A	801.18	4004.57	3524.02	16,699.06	4325.20	17,500.24
Janssen COVID-19	R-134A	598.45	2023.06	1780.29	8436.16	2378.75	9034.62

Figure 4 compares the Vaccine TEWI of a refrigerator to store 100,000 vaccine doses during the equipment lifecycle (10 years), considering a 60% of use factor. Given the difference between the TEWI values of Brazil and the USA, it is verified that the energy mix has a great influence on the environmental impacts. For example, a refrigerator to cold-store the Pfizer–BioNTech vaccine in the USA will emit almost 35-times more CO₂

than that of a refrigerator to cold-store the Oxford–AstraZeneca, CoronaVac or Janssen COVID-19 vaccine in Brazil.

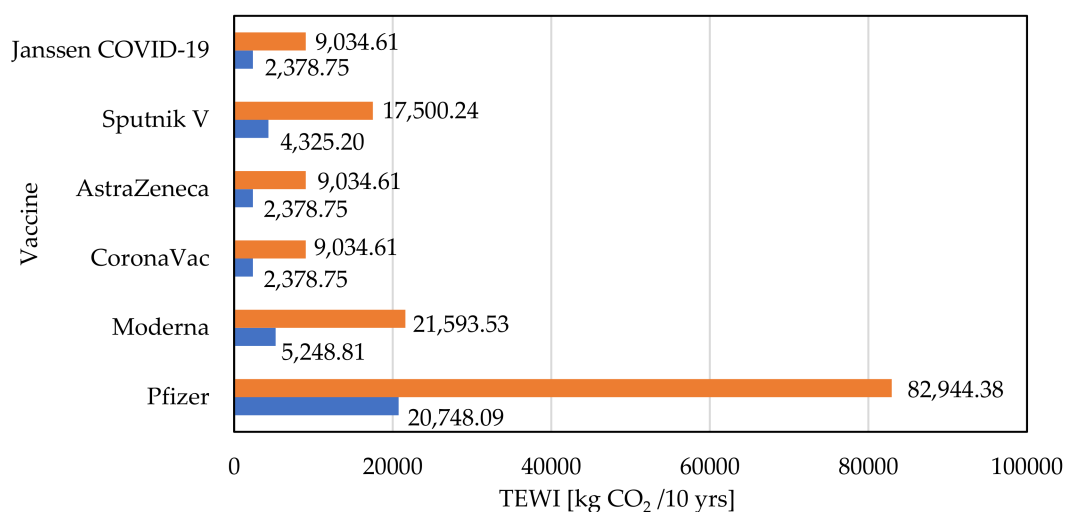


Figure 4. Comparison of TEWI values of 100,000 doses vaccine refrigeration in Brazil and the USA for 10 years. Legend: Brazil: ■ ; USA: ■.

3. Analysis and Discussion of Results

3.1. Worldwide Vaccine EUED

Assuming 14 billion doses, in two semiannual phases of seven billion doses—that is, equivalent to 70,000 in these refrigerators—the Vaccine EUED index worldwide is shown in Table 6. It is important to emphasize that this energy consumption is only related to vaccine cold conservation; it does not consider its manufacturing and transportation. There are several environmental impacts since these vaccines usually need low temperatures and are often transported by plane.

Table 6. Worldwide Vaccine EUED.

Vaccine	Vaccine EUED (MWh/yr)
Pfizer–BioNTech	1,323,325.5
Moderna	347,760.0
CoronaVac	141,614.2
Oxford–AstraZeneca	141,614.2
Sputnik V	280,319.9
Janssen COVID-19	141,614.2

In Brazil, the average annual energy consumption of each individual is 2294.8 kWh, and the energy needed to store the seven billion doses of Pfizer–BioNTech vaccine would be the same as that needed to annually power a city of 576,662 inhabitants. The same calculus for storing the seven billion doses of Oxford–AstraZeneca vaccine would similarly power a city of 61,710 inhabitants [35].

3.2. Worldwide Vaccine TEWI

There are several indications that the vaccine against COVID-19 should be administered annually, due to mutations in the virus [36]. In this case, the use of the Vaccine TEWI indicator in the lifecycle of a refrigeration system is the best way to apply the calculation for a simulation; a lifecycle of 10 years has been used.

Considering the same premise for the Vaccine EUED indicator to meet world demand, 70,000 active refrigerators for 10 years would be needed to acclimatize a demand of

14 billion doses per year in two stages of seven billion semiannually, when comparing the values of Vaccine TEWI in Brazil and the USA; this is shown in Table 7.

Table 7. Worldwide Vaccine TEWI.

Vaccine	TEWI Total Brazil (Ton CO ₂ 10 yr)	TEWI Total USA (Ton CO ₂ 10 yr)
Pfizer–BioNTech	1,452,366.09	5,806,106.98
Moderna	367,416.47	1,511,546.87
CoronaVac	166,512.35	632,423.06
Oxford–AstraZeneca	166,512.35	632,423.06
Sputnik V	302,764.08	1,225,016.55
Janssen COVID-19	166,512.35	632,423.06

A 1.4-L motorized car running 20,000 km/yr emits approximately 7.32 tons of CO₂. In this case, the emission by cars is shown in Table 8 [37]. The comparison with cars allows to compare easily point out the environmental impact of the refrigeration systems for the COVID 19 vaccines. The generation of CO₂ by the refrigerated storage of vaccine from Pfizer–BioNTech in the USA would be equivalent to the circulation of 158,636 cars running 20,000 km, and that the generation of CO₂ by the refrigerated storage of vaccines from Oxford–AstraZeneca, CoronaVac and Janssen COVID-19 vaccine in Brazil would be equivalent to 4549 cars running the same length.

Table 8. CO₂ generated by number of cars in Brazil and the USA.

Vaccine	Number of Cars in Brazil	Number of Cars in the USA
Pfizer–BioNTech	39,682.13	158,636.80
Moderna	10,038.70	41,299.09
CoronaVac	4549.52	17,279.32
Oxford–AstraZeneca	4549.52	17,279.32
Sputnik V	8272.24	33,470.40
Janssen COVID-19	4549.52	17,279.32

Although Tables 6–8 compare the different vaccine brands for the same number of doses, it is important to highlight that the Janssen COVID-19 vaccine requires a single dose [38], while the others require two doses. So, its environmental impact is the lowest.

The same method could be extended to compare other types of vaccines that are under development.

4. Conclusions

This article shows quantitatively the differences between the electricity consumption and pollutant emissions of the refrigeration solutions for various COVID-19 vaccines. In addition to the financial and logistical difficulties, and the assumption that the value of a life cannot be defined, it becomes necessary to use these indicators to help in making important decisions concerning vaccine selection. The associated energy and environmental impact indexes, Vaccine EUED and Vaccine TEWI, respectively, to associate vaccine technologies with energy efficiency and sustainability will have a significant impact worldwide.

All simulations considered refrigerators in air-conditioned locations, but these investments in air-conditioned rooms and ultra-low-temperature refrigerators are rare in developing countries. Nevertheless, these logistical difficulties are also poignant in developed countries due to the delays in vaccination. Considering these options, policymakers should always prioritize low-impact technologies and this article proves that the measurement tools already exist.

The Vaccine EUED and the Vaccine TEWI indexes can be vital tools for decision-making in a second round of immunization as this situation will be the “new normal”.

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