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Evaluating the Energy Efficiency and Environmental Impact of COVID-19 Vaccines Coolers through New Optimization Indexes: Comparison between Refrigeration Systems Using HFC or Natural Refrigerants

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Abstract: COVID-19 vaccines are used worldwide to promote immunity and, in that sense, vaccination is a step forward toward ending the pandemic. Nevertheless, current vaccines must be ultra-cold or cold-stored. Vaccine coolers' energy demand and greenhouse gas emissions lead to a significant environmental impact. This article predicts the environmental and energy impacts of some COVID-19 vaccines: Moderna, Janssen, CoronaVac, Pfizer, AstraZeneca–Oxford–Covishield, and Sputnik V, in terms of carbon dioxide emissions using a new approach for the TEWI (Total Equivalent Warming Impact) methodology, with several options of refrigerants from halogenated to natural fluids such as propane, which is natural gas with low GWP (global warming potential). Through the application of new optimization indexes, it is concluded that the evaporation temperature of the refrigerant gas has a great influence on the sizing of the coolers. For example, for the same number of vaccines, the thermal load of Pfizer is more than double that of AstraZeneca–Covishield, CoronaVac, or Janssen, while the direct environmental impact is seven times greater. Another relevant factor is the choice of refrigerant. For example, the greenhouse effect varies greatly for the same brand of vaccine. The Moderna vaccine's global warming potential (GWP) is 776 times higher using R-449A gas than using R-290 (propane gas). In Brazil, the refrigerators used to store the Pfizer vaccine have a total TEWI almost two times higher than the total TEWI of refrigerators using propane to store the Janssen vaccine. At this time of the pandemic, these optimization indexes can be used to support important decisions regarding the future selection of vaccine brands considering the energy consumption and environmental impact required for their storage.

Keywords: vaccines; SARS CoV-2; COVID-19; environmental impact; TEWI; HFC; propane; energy consumption; EUED

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1. Introduction

Among the actions to reduce deaths from COVID-19 are vaccines, including now for children over 5 years old. "Currently authorized or approved COVID-19 vaccines are effective and safe, reducing the risk of serious illness. The Centers for Disease Control and Prevention (CDC) does not recommend one vaccine over another." Vaccines work to make the body fight infections and protect people by producing immunity. A number of vaccines exist or are being improved with tests (Phases 1, 2, and 3) in the USA [1]. The vaccines include COVID-19 mRNA vaccines and COVID-19 viral vector vaccines. Messenger RNA vaccines are a new type of immunization understudy to protect people from infectious diseases. Like ordinary vaccines, the purpose of messenger RNA is to create antibodies against a virus that threatens human health. However, instead of inserting the attenuated or inactive virus into a person's body, this new immunizer teaches cells to synthesize a protein that stimulates the body's immune response [2]. The benefit of the messenger RNA vaccine is the immunization of the population group, preventing high-risk infections. It should be noted that this new model stands out for other reasons, including agility in synthetic manufacturing, the fact that production is conducted in the laboratory with more accessible materials, flexibility, and reliable immune response with efficacy and safety. These mRNA vaccines are not yet approved for use in Brazil [2].

Viral vector vaccines are developed by inserting the gene that encodes the production of protein S, responsible for binding the new coronavirus with our cells, into another virus, altered so that it is unable to replicate within our body and cause disease or any change in the genome of our cells [3].

The biggest concern of vaccine producers is temperature changes. The storage of these products varies from +2 °C to +8 °C, and any variation can change its effectiveness. This process must be maintained from manufacturing to application and is called the cold chain. In the cold chain, each link must do its part. The laboratory, storage centers, vaccine rooms, and all other participants in this network must carry out storage and transport correctly so that vaccines are never exposed to temperatures outside the established range [4].

A public study conducted in Brazil proved that the most recurrent and important failure in the vaccine cold chain is their exposure to temperatures below +2 °C, to freezing. The study identified the errors that most often cause these failures and undermine the effectiveness of vaccines [4]:

- Practices that exaggerate the protection of vaccines against heat by exposing them to freezing—this problem represented 31% of the failures found;
- Non-specific refrigerators for storing vaccines with temperatures lower than 0 °C—accounted for 21.9%;
- Lack of rigorous temperature monitoring;
- Freezing during transport, which occurred with 75% of vaccines;
- Understanding this weakness in the cold chain, in 2013, the Ministry of Health (MS), through the National Health Foundation (FUNASA), published a version of the Cold Chain Manual [5]. In addition to this, manuals from Australia, England, New Zealand, and the CDC are also used to strengthen good practices in immunizations with different modes of refrigerated storage between different brands.

Both European countries and the United States of America (USA) initially approved the Pfizer–BioNTech and Moderna vaccines [6]. In Brazil, ANVISA approved the CoronaVac and Oxford–AstraZeneca–Covishield vaccines [7]. The Sputnik V vaccine was the first vaccine approved to control the spread of the virus in Argentina. Currently, the last vaccine authorized for use in the USA is Janssen by Johnson&Johnson. To produce the vaccine itself, manufacturing processes are used within the principles of refrigeration and clean rooms, according to regulatory standards. Storage rooms have a security level of BSL-03 (Biosecurity Security Level) [8], with essential air pressure cascades to ensure the safety of users. Assessing electricity consumption and environmental impacts should also be a figure of merit for the decision-making of each country to choose the most relevant vaccine brands. Considering the operational costs and environmental factors, maintaining the stability of the temperature of the vaccines in the storage and transport environment, and preventing the freezing of the immunobiological content are fundamental measures to guarantee the quality of the products during cold storage [5].

According to the manufacturer's specifications for the Pfizer vaccine [9], it must be packaged at a temperature of -70 °C ± 10 °C. The distribution center receives the thermal packages with the vaccines with storage options:

- With ultra-low temperature equipment, which can be purchased on the market, and which will increase the useful life of vaccines by up to 6 months;
- Pfizer thermal transport equipment, which will arrive with vaccine doses. Can be used as a temporary storage unit, refilling with dry ice every 5 days for up to 30 days;
- Refrigeration units in hospitals. In such a unit, vaccines will be stored at a temperature of 2 °C to 8 °C for 5 days, totaling up to 35 days. Once the vaccines have been thawed and stored at these temperatures, they cannot be refrozen. There are several options for vaccination centers, storing Pfizer vaccine in areas with different infrastructure.

The U.S. CDC characterizes Moderna vaccine storage as follows [10]:

- A refrigerator at 2 °C to 8 °C can be used to store vaccine vials for a maximum of 30 days;
- Thawed vaccine cannot be refrozen;
- To track how long the vaccine has been in the refrigerator, a label with the date and other information is used;
- Complete the information on the storage label and attach it to the box that holds the vaccine vials;
- Once labeled, store the vaccine refrigerated;
- For 1 h, store it at room temperature of 15 °C to 25 °C;
- Unused vials can be kept for 12 h at a temperature of 8 °C to 25 °C;
- During transport, the vaccine is frozen from −25 °C to −15 °C and must be kept in storage at this temperature [11].

The Sputnik V vaccine is very robust and withstands storage at a temperature close to −18 °C, a viable temperature in many supply chains [12]. The American CDC states that the Janssen vaccine has a storage temperature between 2 °C to 8 °C [13]. Regarding the CoronaVac vaccine, its storage temperature is that of a common refrigerator, with a working temperature of 2 °C to 8 °C, and may have a shelf life of up to 3 years. This technical specification makes it easier for places with only common refrigerators [14]. Regarding the AstraZeneca–Oxford–Covishield vaccine, the British Government Medicines and Healthcare Products Regulatory Agency provided the following instructions [15]:

- Protect from light;
- A common refrigerator can be used, working between 2 °C to 8 °C;
- Must not be frozen;
- After using the first dose, the vial with the remaining vaccines must be used quickly, within 6 h. When handling it, it should always be stored at a temperature of 2 °C to 25 °C.

Table 1 shows the Sars-Cov-2 vaccines and their minimum storage temperatures.

Table 1. Vaccines and their storage conditions.

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

The electrical energy consumed and the environmental impacts of the equipment, i.e., cold rooms used for refrigeration, must be a concern when deciding on the vaccine brands to select. Important questions must be answered, such as the following:

- What refrigerants are commonly used for these temperatures?
- How can the environmental impact of these devices (cold rooms) be measured?
- What are the attitudes to be taken to reduce environmental impacts, as vaccinations will be constant and more frequent?

This study aims to help answer these questions by presenting the comparison of energy consumption and the environmental impact of the available solutions through a new index proposed in this sense: the Vaccine Energy Usage Effectiveness Design (VEUED) index to measure energy efficiency and environmental impacts of vaccine coolers for COVID-19, as well as to compare the environmental impact through the Vaccine TEWI (Total Equivalent Warming Impact). Additionally, simulated refrigerant gases include propane (R-290), which is a pure component, with no temperature glide, low price, and low GWP, and further being a long-term solution, with high efficiency, naturally not subject to future restrictions, and that is expected to be increasingly used owing to the new IEC 60335-2-89 [16].

2. Materials and Methods

The cooling load of the storage equipment for vaccines must be determined to allow for the comparison of the energy consumption of the cold rooms. Table 2 shows the technical specifications of refrigeration equipment with a capacity for 100,000 doses [17].

Table 2. Typical refrigerated equipment characteristics.

Parameter	Symbol	Unit	Value
Height	H	m	2.05
Length	L	m	1.60
Width	W	m	0.79
Gross volume	V_g	m^3	2.59
Useful volume	V_u	m^3	1.05
Estimated dose capacity	n		100,000
Dose volume	V_d	m^3	3.0×10^{-7}

The equipment has walls with 70 mm expanded thermal insulation panels of injected polyurethane free of chlorofluorocarbons (CFCs) and glass doors. The thermal loads were calculated using the storage temperatures shown in Table 1, assuming an ambient temperature of 24 °C. Overall heat transfer coefficients of the walls and glass were considered as $U_{\text{walls}} = 0.25\ \text{W/m}^2{\cdot}\text{K}$ and $U_{\text{glass}} = 4.0\ \text{W/m}^2{\cdot}\text{K}$, respectively. The number of air changes recommended is 43.5 changes/24 h (Coolpack, University of Denmark). The results are shown in Table 3 [18].

Table 3. Vaccines' cooling load.

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

As vaccines enter the refrigeration equipment, conservation temperatures are adjusted depending on the type and model. In this equipment, the vaccine inlet temperatures (see Table 3) require an air change every 24 h, so an air change factor (ACF) of 43.5 is used.

The coefficient of performance (COP), which is the ratio between the air supply and the consumption of electrical energy, is used to compare the performance of automobile equipment. ASHRAE2-019 (Energy Standard for Buildings, Excluding Low-Rise Residential Buildings) [19] is followed for energy efficiency purposes. There are some parameters for commercial fridges, commercial freezers, and other equipment. The AHRI 1201-2013 standard is used to determine the specific energy consumption [kWh/day]. However, this standard does not apply to vaccines' refrigeration equipment range. Thus, one of the objectives of this study is to create a method to compare these types of equipment. Additionally, energy consumption is evaluated using the Energy Usage Effectiveness Design Index (Vaccine EUED), as is the greenhouse effect, using the Total Equivalent Warming Impact Index (Vaccine TEWI) [20].

There is a need to evaluate some parameters when comparing the efficiency of the refrigeration equipment used for vaccines' storage and conservation. Among them, there is a difference between storage and evaporation temperatures, that is, the difference between condensation and air inlet temperatures. In addition, the isentropic coefficient of the compressor must be considered. A difference of 10 °C between the air inlet and the condensation temperatures should exist, following the AHRI 210/240-2017 [21] standard, because the environments where the vaccine coolers are installed are already acclimatized. Considering the ANSI/ASHRAE 72-2018 standard, the air inlet to the condenser is set to 24 °C at room temperature [22]. Table 4 presents the temperatures and parameters for each vaccine manufacturer in this study.

Table 4. Equipment characteristics according to the vaccine brand.

Vaccines	Inlet Condenser Temperature [°C]	RFCT [°C]	Cold Room Temperature [°C]	RFET [°C]	EFISEN	SHG/SCG
* Pfizer–BioNTech	24	34	−70	−80	0.7	10/3
Moderna	24	34	−25	−35	0.7	10/3
Sputnik V	24	34	−18	−28	0.7	10/3
CoronaVac	24	34	2	−8	0.7	10/3
AstraZeneca–Oxford–Covishield	24	34	2	−8	0.7	10/3
Janssen COVID-19	24	34	2	−8	0.7	10/3

Note: EFISEN = isentropic efficiency; RFCT = refrigerant fluid condensation temperature; RFET = refrigerant fluid evaporation temperature. * Specifically in the ultra-low temperature freezer, evaporation of fluid R-508B is −80 °C and the condensing temperature is −30 °C. The evaporation temperature of R-449A is −40 °C, for a plate heat exchanger approach of 10 K [23].

Table 5 shows the classes defined by ASHRAE [24] standards, temperature classes, and other systems used for the transport and storage of these vaccines. These are not vaccine-specific limits, as per the CDC. Each manufacturer has its guidelines regarding the conservation temperature range. In this work, propane (R-290) was used as an alternative refrigerant.

Table 5. Vaccine transport and storage systems and classifications.

Temperature Class	Typical Range (°C)	Vaccines	Common Storage Systems	Common Transport Systems
Medium Temperature Refrigeration	2 to 8 †	• Janssen • inactivated vaccines • LAIV	• Purpose-built vapor-compression refrigerators • cold rooms	• Purpose-built unit load devices (air), • Refrigerated containers (sea, rail, road), • Qualified containers and packets, • Passive cooling devices

Table 5. *Cont.*

Temperature Class	Typical Range (°C)	Vaccines	Common Storage Systems	Common Transport Systems
Low Temperature Refrigeration	−50 to −15	• Moderna • Varicella • MMRV • zoster	• Purpose-built vapor compression freezers • freezer rooms	• Purpose-built refrigerated containers (sea, rail, road), • Qualified containers and packets, • Passive cooling devices
Ultra-Low Temperature Refrigeration	−80 to −60	• Pfizer–BioNTech • Ervebo	• Purpose-built vapor compression cascade • Cascade	• Purpose-built refrigerated containers (sea, rail, road) • Passive cooling devices

† Danger of freezing and refreezing vaccines requires special attention.

The COP measurement parameters are determined considering the refrigerant. The following recommendations should be followed:

- The Kigali protocol [25] encourages that refrigerants with low global warming potential (GWP) are used. As an example, propane (R-290) is a natural refrigerant that has a low GWP = 3. Conversely, refrigerants such as R-134A have a medium GWP = 1430 and R-404A has a high GWP (GWP = 3922) [24].
- The use of refrigerants with null ozone depletion potential (ODP) is encouraged by the Montreal protocol, disregarding the elimination of refrigerants such as R-12 and R-502 [26].
- It is not usual to find vaccine refrigerators using natural refrigerants. As an example, an ammonia system is not used in small systems because of its complexity and dangerous toxicity [27].

Good distribution requires systematic cost-effectiveness analysis and operational planning. All cold storage facilities for vaccines must have 100% reserve refrigeration capacity, i.e., the rooms must have backup equipment. The World Health Organization (WHO) establishes the first initial and primary steps for vaccine [28] stocks. R-134A fluid is normally used in cold rooms at +4 °C, but is not suitable for cold rooms at −20 °C. R-404A is an alternative refrigerant available for this purpose. Although it is already being discontinued (R-404A fluid cannot be used in new equipment, although recovered R-404A can be used until 2030), it is still used in many systems (small equipment, packaged equipment, and medium-sized multi-compressor equipment). In most cases, this refrigerant is replaced by new low GWP refrigerants such as R-455A, R-454C, and R-1234yf. R-134A is the refrigerant used in refrigeration systems for cold storage of AstraZeneca–Oxford–Covishield, CoronaVac, and Janssen COVID-19 vaccines. R-449A (low GWP compared with R-404A) is the refrigerant used in the Sputnik V and Moderna refrigeration systems. For the Pfizer–BioNTech vaccine, R-508B refrigerant with special refrigerant and ultra-low temperature evaporation applications associated with R-449A is considered. When it comes to ultra-low temperatures, the cascade system is the most suitable [29]. The study predicts the use of low GWP refrigerants, such as R-449A, but knowing that R-404A is still widely used. Table 6 shows the refrigerant selected for each vaccine's refrigeration system considering the thermal specifications, its GWP, refrigerant charge, and equivalent CO_2 emissions.

Table 6. Vaccines, refrigerants, and GWP.

Vaccines	Refrigerant(s)	GWP	Load Refrigerant Gas (kg)	CO_2 kg
Pfizer	R-508B & R-449A	13,396 & 1430	0.15 + 0.45	2652.9
Moderna	R-449A	1397	0.405	565.785
Sputnik V	R-449A	1397	0.37	516.89
CoronaVac	R-134A	1430	0.27	386.1
AstraZeneca	R-134A	1430	0.27	386,1
Janssen	R-134A	1430	0.27	386.1
Pfizer	R-508B & R-290	13,396 & 3	0.15 + 0.15	2010.21
Moderna	R-290	3	0.243	0.729
Sputnik V	R-290	3	0.243	0.729
CoronaVac	R-290	3	0.162	0.486
AstraZeneca	R-290	3	0.162	0.486
Janssen	R-290	3	0.162	0.486

The cooling loads of the different solutions of refrigerants for vaccine coolers were simulated in the Laboratory of the Faculty Professional—FAPRO in Curitiba-Paraná, Brazil. The environmental impact given in terms of CO_2 emissions is shown in Figure 1, assuming the use of the initial charge of R-449A refrigerant. As shown in Table 3, the cooling load of the Pfizer–BioNTech vaccine is more than two times greater than the cooling load of the CoronaVac, AstraZeneca–Oxford–Covishield, and Janssen COVID-19 vaccines. Thus, the environmental impact due to the refrigerant required to meet the storage temperature has a difference of almost 7 times with R-449A, as shown in Table 6 and Figure 1. For propane, this difference rises to 417 times [30,31]. In this specific case, the refrigerant charge required is smaller (40% small).

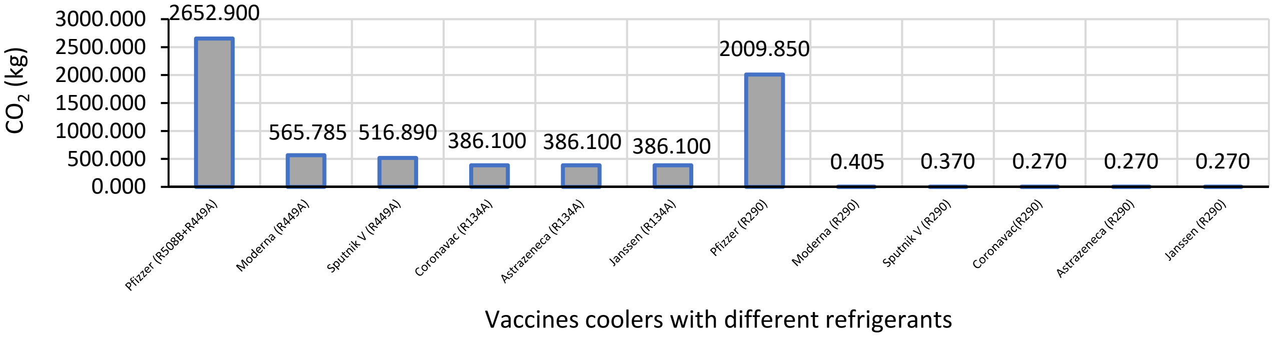

Figure 1. Environmental impact (equivalent CO_2 emissions) for different vaccines' refrigeration systems.

After determining the thermal and refrigerant requirements, the next step is to calculate COP. A special refrigerant is required in ultra-low temperature refrigerators. For this simulation conducted with Chemours, Expert 1.0 software [32], R-508B refrigerant was used. The COP of refrigeration systems for vaccines with condenser fans and evaporators is shown in Figure 2.

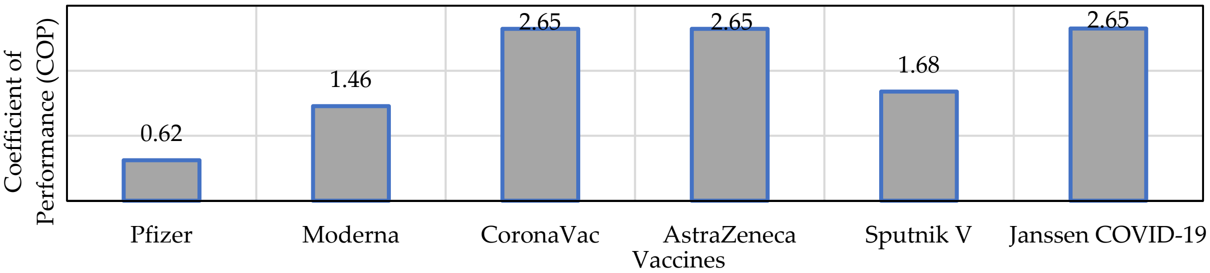

Figure 2. COP of refrigeration systems with evaporator and condenser fans for vaccines.

2.1. Vaccine Energy Usage Effectiveness Design (Vaccine EUED) Index

Santos et al. [33–38] proposed the Energy Usage Effectiveness Design (EUED) index to measure the energy efficiency in data centers (DCs). A broader and more global view of energy consumption, emphasizing the environment, is given by this index [39–41]. The index provides an analysis involving all the natural parameters of the region where the system will be installed (dry and humid air bulb temperatures, soil temperature, and air dew point temperature). The EUED index (Equation (1)) was developed to be used in the design phase to predict energy efficiency.

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

Santos et al. [42] demonstrated the differences between electricity consumption and the environmental impact of cooling solutions for various COVID-19 vaccine brands. The simulations considered refrigerators placed in air-conditioned locations. It must be highlighted that equipment with ultra-low temperatures and air-conditioned space may be unusual in developing countries. The decision-making in the immunization approach, as this situation will be the “new normal”, can be supported by the Vaccine EUED and Vaccine TEWI indices [42].

Applying meteorological data from 8760 h per year, the EUED index provides a result suggesting the use of an evaporative system, variable COPs, or a free cooling system.

The index was adapted for vaccine refrigeration equipment. The condensation temperature was considered constant. The experimental tests carried out in the FAPRO laboratory encountered some operational peculiarities. The cost of R-508B is extremely high and it is not available in Brazil. In addition, working in ultra-low temperatures requires suitable protective clothing to prevent work-related accidents. Furthermore, the compressor operated from the lowest to the highest threshold of the cooling load of vaccine coolers during 60% of the operation time. For example, after reaching the thermal equilibrium, the AstraZeneca–Oxford–Covishield, Janssen COVID-19, and CoronaVac vaccines stored at +8 °C and kept at +2 °C have a heat load composed of the infiltration and conduction loads. Equation (2) defines the Vaccine EUED:

$$\text{Vaccine EUED} = \left(\frac{\text{Thermal Load } [\text{kW}]}{\text{COPcomplete } \left[\frac{\text{kW}}{\text{kW}}\right]} \right) \cdot \text{Load Factor } (\%) \cdot 8760 \text{ h} \tag{2}$$

Table 3 shows the thermal load used in calculations. Figure 1 shows the COP values. The Vaccine EUED index shown in Figure 3 considers a compressor load factor of 0.6 and 8760 h of operation. It represents the annual energy consumption of each vaccine in the refrigeration system. There are substantial differences between the EUED index for vaccine storage. For example, a vaccine refrigeration system for the Pfizer–BioNTech vaccine has an energy consumption 9 times higher than a vaccine system for Janssen COVID-19, CoronaVac, and Astra-Zeneca–Oxford–Covishield vaccines.

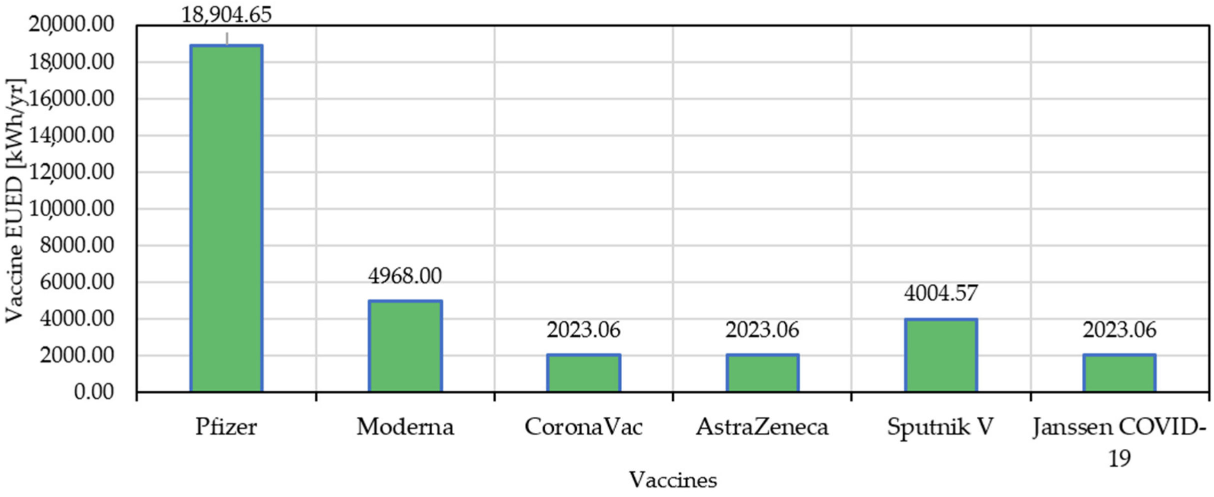

Figure 3. Vaccine Energy Usage Effectiveness Design (EUED) index.

2.2. Vaccine TEWI—Total Equivalent Warming Impact

The Total Equivalent Warming Impact (TEWI) is a metric of the global warming impact with total emissions related to the global warming impact (GWP) of equipment during equipment use and end-of-life removal of operating fluids. of the system. TEWI considers indirect and direct emissions [43]:

- Direct Emission—Refrigerant released in the lifetime of the equipment, including losses not recovered at the destination.
- Indirect Emission—CO_2 emissions of fossil fuel systems to generate the electric energy used throughout its useful life.

TEWI index is given by Equations (3) and (4):

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

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

where:

EOL = end of life
GWP = global warming potential relative to CO_2 (GWP CO_2 = 1)
n = system operating life (yrs)
L_{annual} = leakage rate p.a. (kg)
m = refrigerant charge (kg)
$\alpha_{recovery}$ = recovery/recycling factor from 0 to 1
β = indirect emission factor (kg CO_2/kWh)
E_{annual} = energy consumption per year (kWh p.a.)

The results show that refrigerants have, proportionally, a greater impact in Brazil than in other important cities in the world.

The indirect emission factor, β, varies according to the energy matrix. In Brazil, the energy system matrix across the country is balanced. According to the National Energy Balance (BEN), Brazil emits 0.088 kg CO_2/kWh [44]. According to the Energy Information Administration (EIA) [45], the United States of America emits 0.417 kg CO_2/kWh. The Vaccine TEWI index on a 10-year cycle, using TEWI concepts in addition to the Vaccine EUED index, is given by Equation (5) [46].

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

Table 7 shows the TEWI of each vaccine refrigeration system for the USA and Brazil.

Table 7. Indirect and direct TEWI of each vaccine refrigeration system for the USA and Brazil.

Vaccines	CO_2 kg	EUED (kWh/yr)	TEWIe Direct	TEWI Indirect Brasil	TEWI Indirect USA	TEWI Total Brazil	TEWI Total USA
Pfizer	2652.90	18,904.65	4112.00	16,636.09	78,832.39	20,748.09	82,944.39
Moderna	565.79	4968.00	876.97	4371.84	20,716.56	5248.81	21,593.53
Sputnik V	516.89	4004.57	876.97	3524.02	16,699.06	4400.99	17,576.02
Coronavac	386.10	2023.06	598.46	1780.29	8436.16	2378.75	9034.62
AstraZeneca	386.10	2023.06	598.46	1780.29	8436.16	2378.75	9034.62
Janssen	386.10	2023.06	598.46	1780.29	8436.16	2378.75	9034.62
Pfizzer (R-290)	2010.21	18,904.65	2780.36	16,636.09	78,832.39	19,416.45	81,612.75
Moderna (R-290)	0.73	4968.00	1.13	4371.84	20,716.56	4372.97	20,717.69
Sputnik V (R-290)	0.67	4004.57	1.13	3524.02	16,699.06	3525.15	16,700.19
Coronavac (R-290)	0.49	2023.06	0.75	1780.29	8436.16	1781.05	8436.91
AstraZeneca (R-290)	0.49	2023.06	0.75	1780.29	8436.16	1781.5	8436.91
Janssen (R-290)	0.49	2023.06	0.75	1780.29	8436.16	1781.05	8346.91

Figure 4 compares the Vaccine TEWI for refrigerators to store 100,000 doses of vaccine over the life of the equipment (10 years), considering a usage factor of 60%. After determining the difference between the TEWI values for the USA and Brazil, it is verified that the energy matrix has a huge influence on environmental impacts. For example, a refrigerator to store the Pfizer–BioNTech vaccine in the USA will emit almost 35 times using R-449 and 46 times using Propane (R-290) more CO_2 than a refrigerator to store the AstraZeneca–Oxford–Covishield, CoronaVac, or Janssen COVID-19 vaccines in Brazil.

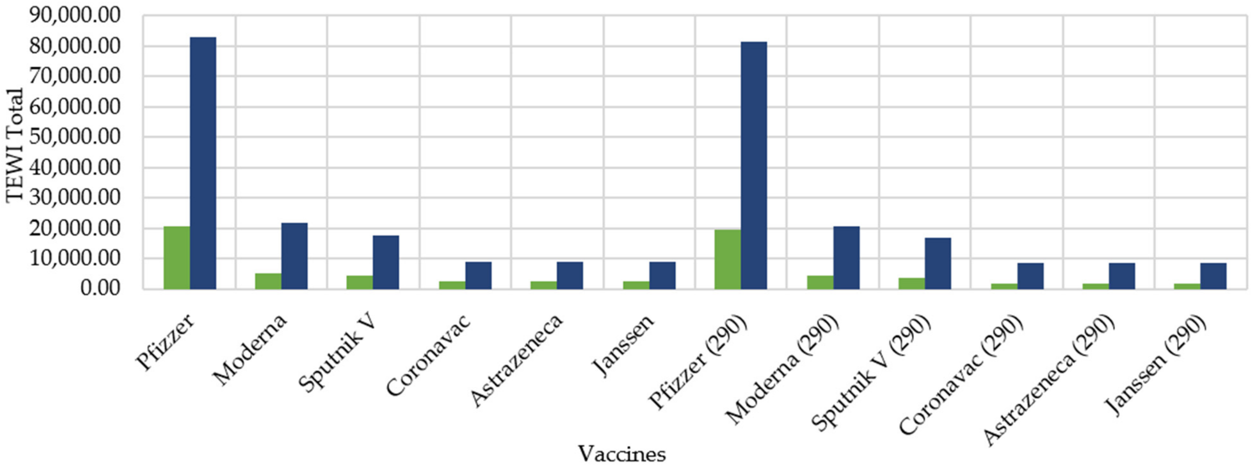

Figure 4. Comparison of total refrigerated TEWI values of 100,000 doses of vaccines in the United States and Brazil for 10 years. Caption: Brazil: 🟩; USA: 🟦.

3. Discussion and Analysis of Results

3.1. Vaccine EUED World Yearly

The Vaccine EUED index, assuming 14 billion doses, in 7 billion doses per semester, which is the equivalent of 70,000 refrigerators, is given in Table 8. It is important to emphasize that this energy consumption is only related to vaccine cold conservation, disregarding manufacturing, and transport. There are numerous environmental impacts due to low temperature storage and airplane transport.

Table 8. Vaccine EUED world yearly.

Vaccines	Vaccine EUED [MWh/yrs]
Pfizer–BioNTech	1,323,325.5
Moderna	347,760.0
Sputnik V	280,319.9
CoronaVac	141,614.2
AstraZeneca–Oxford–Covishield	141,614.2
Janssen COVID-19	141,614.2

The average annual energy consumption in Brazil per inhabitant is 2294.80 kWh. Thus, the energy consumed to store the 7 billion doses of the Pfizer–BioNTech vaccine would be equal to annually supplying energy to a city with 576,662 inhabitants, the size of Londrina in Paraná—Brazil. The same calculation to store the 7 billion doses of the AstraZeneca–Oxford–Covishield vaccine would similarly supply a city of 61,710 people. [45].

3.2. Vaccine TEWI World Yearly

As the disease evolves, it is noted that there are mutations in the virus, and with that, COVID 19 vaccines will be administered [47]. In this case, the best way to apply the calculation for simulating the Vaccine TEWI index is its useful life of a refrigeration system (assuming a life cycle of 10 years).

Considering the same assumptions used to calculate the Vaccine EUED index to meet the world demand, for 14 billion doses, it would take a demand of around 70,000 active refrigerators for 10 years to store two-phase doses of 7 billion every 6 months. The comparison of Vaccine TEWI values for the USA and Brazil is shown in Table 9.

Table 9. Vaccine TEWI world yearly.

Vaccines	TEWI Total Brazil [ton CO_2 10 yrs]	TEWI Total USA [ton CO_2 10 yrs]
Pfizer–BioNTech	1,452,366,090	5,806,106,985
Moderna	367,416,472.5	1,511,546,873
Sputnik V	166,512,346	632,423,064
CoronaVac	166,512,346	632,423,064
AstraZeneca–Oxford–Covishield	302,764,077	1,225,016,548
Janssen COVID-19	1,359,136,590	5,712,877,485
Pfizer–BioNTech (R290)	306,072,742.5	1,450,203,143
Moderna (R290)	124,649,791	590,560,509
Sputnik V (R290)	124,649,791	590,560,509
CoronaVac (R290)	1,246,721,657	1,168,974,128
AstraZeneca–Oxford–Covishield (R290)	1,452,366,090	5,806,106,985

4. Conclusions

This study reveals the differences such as electricity consumption and the greenhouse effect of refrigeration solutions for various brands and types of vaccines for COVID-19, not considering the logistics adversities. At this time of the pandemic, it is necessary to use indicators to support important decisions regarding the selection of vaccine brands. Energy and greenhouse indicators were defined as Vaccine TEWI and Vaccine EUED, respectively, to associate vaccine technologies with energy efficiency and sustainability in a globalized world.

The simulations were carried out considering the refrigerators in acclimatized locations. Given these options, public administrators should always prioritize low-impact technologies, and this study proves that measurement tools already exist.

It is important to emphasize the priority of using natural gases such as propane, because, from a general point of view the Pfizer, Moderna, Sputnik V, CoronaVac, AstraZeneca-

Oxford-Covishield, and Janssen vaccines, using propane gas has a reduction in the overall TEWI of 1.07, 1.20, 1.25, 1.33, 1.33, and 1.33 times, respectively, in Brazil. These differences over the 10-year lifetime are considerable. A detail to be considered in the conclusions is that all were compared with two annual doses; the Janssen vaccine has the possibility of an annual dose, but there are already countries with two annual doses of Janssen [48].

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