Energy Requirements of the Screening Sites in a COVID-19 Hub and Spoke Testing Approach

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Introduction and Objective

This note outlines the energy requirements for COVID-19 screening sites to provide information to those who are working to build testing capacity in off-grid and weak-grid areas.

As the spread of COVID-19 increases globally, the need for more readily available testing sites with reliable energy supplies has become necessary, especially in regions where a significant portion of the population lives with limited or no access to the electrical grid. The objective of this note is to provide information about the energy requirements of COVID-19 screening sites, or the "spokes" in the context of a "hub and spoke" testing approach.[1]

This widely used approach involves a centralized test lab (the "hub") and distributed screening locations (the end points of the "spokes"). While the central test labs will often be large state, regional, or national labs, the screening sites could include smaller hospitals, COVID treatment centers, and potentially rural health clinics, or "pop-up" sites.

Under this approach, samples collected at the screening sites must be stored temporarily onsite and then transported to the testing center for processing. The most significant energy requirements associated with screening and transportation are linked to the need to maintain collected samples within a temperature range.[2] The cooling requirements for this model are similar to those associated with the distribution of vaccines, and it may be possible to utilize existing vaccine cold chain infrastructure to support the COVID-19 testing process in some geographies.

This note outlines the energy requirements for COVID-19 screening sites to provide information to those who are working to build testing capacity in off-grid and weak-grid areas. Health professionals may be most interested in the first five sections:

1. Screening Process and Sample Storage Requirements
2. Options to Maintain Cold Chain
3. Sample Transportation
4. Utilization of Existing Vaccine Cold Chains
5. Refrigerator / Freezer Sizing and Selection

Energy sector professionals should also review the final section along with the previous ones:

6. Power and Energy Considerations

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1 This guidance note was prepared by Margaret Harper, Tyler Bernard, Amy Sprowles, and Arne Jacobson of Humboldt State University and the Schatz Energy Research Center. The content draws heavily from resources published by the World Health Organization (WHO). Additional input and review of this note was provided by Gopal Nadadur and Cynthia Liao from the Clinton Health Access Initiative (CHAI), Nithya Ramanathan of Nexleaf Analytics, Maia Cheli from Humboldt State University, and Raluca Golumbeanu, Rahul Srinivasan, Stephen Dorey, Samira Elkhamlichi, Daron Bedrosyan, Chris Greacen, Chris Purcell, Jennifer Lynch, and other members of the World Bank/ESMAP team.

2 The central laboratory (or "hub") also has substantial energy needs, but details on these needs are not included in this note. Test labs will require a reliable energy supply to operate. Energy is also associated with the mode of transportation used, whether it be shipping by land or air, or travelling with samples in a car or bus. However, this note is focused on the energy required for refrigeration and/or freezing associated with COVID screening.

1. Screening Process and Sample Storage Requirements

RT-PCR (reverse transcription-polymerase chain reaction) testing is the most common type of testing used for COVID-19 screening to date. This assay is dependent on the ability to isolate COVID-19 genetic material from the patient's respiratory system, often from the use of nasopharyngeal swabs to obtain respiratory secretions. Samples are typically collected in Viral Transport Medium (VTM) consisting of fetal bovine serum with antibiotic and antifungal supplements, or the proprietary Universal Transport Medium (UTM). However, due in part to the shortage of the reagents for these media, sterile phosphate buffered saline (PBS) has been approved as an acceptable substitute [1].

Once samples are collected, they can either be stored in the range of 2-8°C or frozen to -20°C to -70°C.[3] Depending on the type of specimen, samples remain stable at 2-8°C for 24 hours to 5 days after collection, while frozen samples can remain stable for longer periods (see Annex A for storage requirements based on the specimen type and test equipment). Storage above 8°C and/or repeated freezing and thawing of collected samples should be avoided, as these conditions can lead to inaccurate test results.

Additionally, the temperature requirements of the test kits should be considered. Testing kits that are based on VTM must be kept refrigerated. For testing kits that use either UTM or sterile saline, the kits can be stored at room temperature prior to the collection of specimen, but the samples must be refrigerated after collection.[4]

2. Options to Maintain Cold Chain

Storage above 8°C and/or repeated freezing and thawing of collected samples should be avoided, as these conditions can lead to inaccurate test results.

To meet test kit and sample temperature requirements, there are three primary options a screening site can employ:

1. Use a refrigerator able to maintain the samples at 2-8°C for short-term storage, along with a freezer or separate freezer compartment to freeze and store ice packs for transportation. If the test kits must also be refrigerated prior to testing, they must be kept separate from samples that have been collected to avoid contamination, so two refrigerators/insulated containers, or a refrigerator designed with separate or clearly labeled compartments, would be needed in this case.

2. Use a freezer that is able to keep samples frozen between -20°C and -70°C and is able to freeze and store ice packs for transportation. Ice packs should be frozen in a separate freezer or freezer compartment to minimize the temperature fluctuation of samples while ice packs are freezing.

3 For frozen samples, the WHO recommends freezing to -70°C and shipping at that temperature with dry ice. However, given the limited availability of dry ice and -70°C freezers, some practitioners suggest freezing samples using a conventional freezer to -20°C. Specimens frozen to -70°C are viable for longer than those frozen to -20°C.

4 Antibody testing may also be an important element of COVID-19 testing efforts, but these cannot be used to identify active infections and are not the focus of this memo. The kits for antibody testing may need to be refrigerated before use, depending on which type of test kits are used. They should not need to be stored after testing, as the results are available quickly. Similarly, other methods of rapid testing for active COVID-19 infections, such as lateral flow assays, are under development, though the accuracy of these tests has not yet been confirmed. If a low-cost, accurate, rapid test is developed and widely deployed, the need to ship refrigerated or frozen samples to centralized test laboratories may be reduced.

3. In cases where refrigeration is unavailable, but where ice packs can be regularly supplied, heavily insulated stationary vaccine containers could be considered. These containers are often called "passive" containers as they rely solely on ice packs for cooling, with no onboard energy source. Several devices are available that can maintain refrigerated temperatures for 10 to 35 or more days before requiring new ice packs [3]. Similarly, if dry ice is attainable, it may be possible to use an insulated container with dry ice, where the insulated container is delivered and picked up regularly. These strategies could work if the samples and ice packs (or dry ice) can be picked up and restocked routinely.

The costs of these three options will depend on the selected equipment and the availability of reliable electricity at the site.

3. Sample Transportation

For transportation purposes, the World Health Organization (WHO) currently recommends the use of insulated containers with ice packs to keep samples at the correct temperature (see Figure 1 for an example) [4,5]. For refrigerated samples, ice packs should first be "conditioned," where ice packs are exposed to room temperature for 30 to 120 minutes until there is liquid water inside every pack and the ice cores are able to move freely inside each pack. This process will better ensure that samples are not inadvertently frozen and thawed during transport, but instead maintained at the target temperature of 2-8°C.[5]

Figure 1. Example of a vaccine transport container with ice packs or cool water-packs designed to maintain 2-8°C for over 12 hours ©GiveWell

Refrigerated coolers that plug into DC car outlets can also be used, but they are expensive and require a reliable source of electricity at all times during transport. Lastly, though they are more expensive and are less standardized than ice packs, eutectic packs (phase change materials) that freeze at positive temperatures (e.g. +5°C) may be used instead of ice packs to prevent unwanted sample freezing.[6]

For transporting frozen samples, or for cases where transportation of samples will take more than 2-5 days, dry ice is recommended, but is unlikely to be available in rural, off-grid geographies. In lieu of dry ice, frozen ice packs (without conditioning) should be used in an insulated container.

5 Given the risk of non-compliance with correct frozen water-pack conditioning, the WHO notes that for freeze-sensitive vaccines, it is possible to use cold water-packs (+2 to +8°C). Depending on the model, the cool life of an insulated container using cold water-packs instead of frozen ice packs varies from 4.5 to 18 hours. Therefore, if the duration of transport falls within the cool life of the available container, cold water-packs could be used instead of frozen ones to avoid the risk of freezing samples during transport, though sample temperatures are likely to rise above 8°C. [4]

6 In the latest Performance Quality and Safety (PQS) catalog, the WHO indicates that they may begin to approve eutectic packs in the future, but they have not approved any yet for use with vaccines [5].

For transport of samples with frozen and conditioned ice packs, WHO recommends the use of insulated containers with a published cold life at least as long as that required for the longest planned transport leg, measured from the time of packing the container at the screening site to the time of unpacking at the testing site [4].[7] For transport of samples with conditioned ice packs, it is important to understand that some cold life is lost during the conditioning process. A safety margin should be included in the estimate of the transportation time to address pack melting rate, possible transport delays, and variations in the environmental conditions.

4. Utilization of Existing Vaccine Cold Chains

As noted in the introduction, the temperature requirements for both storage and transport of samples are very similar to those of vaccines.

Immunization programs in many countries – typically with support from the Gavi Alliance – have established vaccine cold chains consisting of vaccine refrigerators, freezers, and cold boxes (refrigerated or insulated containers). These existing cold chains could potentially be partially re-purposed to enable the storage and transport of COVID-19 screening samples.

Use of these existing cold chains will need to ensure that samples can be safely stored without cross-contamination, while minimizing disruption of existing vaccination efforts (how these precautions can be achieved is still under discussion). In the absence of a functional vaccine cold chain or a safe method to use the existing cold chain, screening centers will need to have access to freezers, or to refrigerators that can maintain samples at 2-8°C, and a method to transport the samples, either via refrigerated coolers or a freezer to maintain ice packs for shipping.

It should be noted that management of the vaccine cold chain is typically a responsibility of a country's Ministry of Health, often with support of the WHO, UNICEF and Gavi Alliance. Therefore any and all decisions affecting either cold-chains or associated logistics require buy-in and approval from those managing the existing vaccine cold chain.

5. Refrigerator / Freezer Sizing and Selection

Confirmation of refrigeration sizing requirements will be based on input from public health officials in the respective countries and on a screening site's expected volume of testing. For example, for 72 collected samples, a rack that holds 72 units of 3-ml conical sample collection tubes would be about 10.4 cm wide, 20.3 cm long, and 8 cm tall (counting the height of the tubes and the rack used for this example), which is equivalent to a volume of approximately 1.7 L.

7 According to the WHO, the "cold life" of a container loaded with frozen ice packs is the time from when the container lid is closed until the temperature of the warmest point in the vaccine storage compartment first reaches +10°C, at a constant ambient temperature of +43°C. Similarly, the "cool life" of a container is conducted with cool (5°C) water-packs, and is measured as the time until the vaccine compartment reaches +20°C [4]. These values are listed for containers tested and included in the WHO PQS catalog [5].

Confirmation of refrigeration sizing requirements will be based on input from public health officials in the respective countries and on a screening site's expected volume of testing.

Other sample collection tube sizes (e.g. 13 mm x 100 mm 10 ml tubes stored in a similar rack with a total volume of 2.1 L) may also be used, depending on the recommendations of the testing system manufacturer. In many cases, a small refrigerator or freezer should be sufficient for storing samples, while a second freezer or separate freezer compartment could be reserved for freezing and storing ice packs.

The WHO provides a list of refrigerators, freezers, and insulated containers which have been tested and prequalified to be used for vaccine storage and transport.[8] Given the need to maintain samples at the specified 2-8°C temperature range, it is recommended to use devices on this list. Currently, most devices listed are either ice-lined refrigerators intended for use with an intermittent grid or generator, or solar direct drive refrigerators that are powered directly from solar photovoltaic (PV) modules without battery storage. As of April 2020, only two listed devices were designed to be used with a PV/battery DC system.[9]

In cases where a suitable refrigerator is not available from this list, domestic refrigerators may be considered, but need to be tested against the WHO Performance Quality and Safety (PQS) verification protocol to confirm that they meet the requirements [5]. Units that use the freezer air to cool the refrigerated space, and units with a single door that opens both the refrigerator and freezer compartments are not suitable due to the lack of adequate temperature control. The majority of domestic refrigerators will not adequately maintain temperatures for storage of sensitive vaccines or test samples and will therefore not meet the WHO PQS requirements.

The WHO PQS catalog also lists suitable combined refrigerator/freezers and freezers that can be used to quickly freeze ice packs. However, for a stand-alone freezer being used to solely freeze ice packs, and not for sample storage or rapid deployment of ice packs, domestic freezers should be considered because they usually cost less, can be procured locally, are delivered quickly, and spares and technical expertise are more readily available [5].

In addition to refrigerators, freezers and insulated containers, the WHO PQS catalog also includes lists of voltage regulators and temperature monitoring devices that can help ensure performance of cold chains, as well guidance on procurement of spare parts and training that can improve the long-term operation and maintenance of the systems.

6. Power and Energy Considerations

The choice of device type should be based on the available energy source(s). Facilities with reliable electricity (from the electric grid, a generator, or a PV/battery/generator hybrid system) can use any reliable type of refrigerator that meets the WHO PQS requirements.

Facilities with unreliable electricity, but that receive at least eight hours of electricity per day, may be able to reliably operate certain ice-lined refrigerators or refrigerator/freezers which are designed to maintain cool temperatures during power outages.

8 The list is available in the "PQS Catalog": https://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/ [5].

9 The decline in inclusion and use of these systems is due to their high costs and poor long-term performance in the field without proper battery maintenance and battery replacement. The WHO now recommends that solar direct drive refrigerators be used in cases where off-grid electricity is required.

In cases where a facility receives less than 8 hours of electricity per day or where electricity access is unpredictable, solar vaccine refrigerator systems should be considered [3,6]. Note, for sites with between 4 – 8 hours of electricity per day on a predictable basis, certain ice-lined refrigerators may be appropriate, though often a separate solar direct drive refrigerator would be recommended.

In cases where a facility receives less than 8 hours of electricity per day or where electricity access is unpredictable, solar vaccine refrigerator systems should be considered.

See Annex B for a useful flowchart that provides guidance for selecting a device based on the available energy source. When using a PV/battery DC system or a solar direct drive system, unless equipped with an approved "Solar Energy Harvest Controller," the PV panels and battery packs which power the refrigerator must be used for this purpose alone to ensure the refrigerator or freezer receives the energy needed to maintain a constant temperature.[10]

The energy requirements for refrigerators and freezers vary substantially between models and do not demonstrate a clear relationship between energy use and volume. As shown in Table 1, refrigerators listed in the April 2020 WHO PQS catalog vary in energy consumption per day between 0.54 kWh/day and 5.1 kWh/day, depending on the type refrigerator, the energy efficiency, and whether it is operating at a stable running temperature, or in the process of cooling down (or freezing the internal ice, in the case of ice-lined refrigerators).

For freezers, energy consumption during freezing varies from 0.81 kWh/day to 4.36 kWh/day. For facilities considering adding refrigeration/freezing to an existing electric grid, generator, or solar-generator hybrid system, this additional energy should be considered in the system design or expansion.

Health center in Djinginiss, Niger ©Chris Carlsen

10 WHO has developed specifications for Solar Energy Harvest Controllers, which would allow excess energy supplied by the PV modules to be used for other purposes while ensuring the required energy for the refrigerator [5].

Table 1. Energy consumption of refrigerators and freezers in WHO PQS catalog

Type of appliance	Number of units in WHO PQS catalog	Range of refrigerator energy consumption considering both stable running and cool-down operation (kWh/day)	Average refrigerator energy consumption during stable running (kWh/day)	Average refrigerator energy consumption during cool-down (kWh/day)	Range of energy consumption during freezing (kWh/day)	Average energy consumption during freezing (kWh/day)
Battery solar powered combined refrigerator and freezer	1	--	0.58 (n=1)	1.23 (n=1)	--	0.99 (n= 1)
Combined icelined refrigerator/ waterpacks freezer	4	0.7 - 4.34	1.50 (n=4)	2.21 (n=4)	0.97 - 1.95	1.66 (n=4)
Icelined refrigerator	27	0.54 - 5.10	1.22 (n=27)	1.65 (n=26)	--	--
Solar direct drive combined refrigerator/freezer	11	--	0.72 (n=1)	0.72 (n=1)	--	0.81 (n= 1)
Solar direct drive freezer	3	--	--	--	--	--
Solar direct drive refrigerator	27	--	--	--	--	--
Two mode battery solar refrigerator OR freezer	1	--	1.01 (n=1)	2.15 (n=1)	--	2.35 (n=1)
Two-mode vaccine refrigerator OR waterpacks freezer	1	--	1.37 (n=1)	1.32 (n=1)	--	3.91 (n=1)
Vaccine/waterpacks freezer	8	--	--	--	3.33 - 4.36	3.85 (n=5)

Note: Most solar direct drive appliances and some freezers did not have energy consumption data reported in the WHO PQS. The numbers in the first column of the table indicate the total number of that type of appliance that were listed in the April 2020 WHO PQS catalog, while the sample size (n=...) next to each average indicates the number of appliances with an energy consumption listed and included in the average or range.

According to the listing in the PQS Catalog, a PV system for a medium-sized (100 L) solar direct drive refrigerator/freezer would be approximately 0.6 kW. However, this estimate should be taken with caution, as sizing of PV arrays for solar direct drive refrigerators is highly dependent on the specific appliance, the ambient temperature, and the available solar insolation at the site.

Another aspect to consider when choosing a refrigerator/freezer is the refrigerant used in the device. Nineteen of the devices listed in the PQS catalog use a refrigerant called R134a, which has a high global warming potential (GWP100) of 1300 (i.e., over 100 years, the release of one gram of R134a would have the same impact as 1300 grams of CO2 if climate-carbon feedbacks are not considered) [7].

Considering devices with low global warming potential (GWP) refrigerants and high energy efficiency will minimize the climate impact of new installations.

The PQS catalog also lists the 62 devices which use isobutane (R600a) and two devices which use propane (R290) as refrigerants, both of which have low GWPs [8]. Considering devices with low GWP refrigerants and high energy efficiency will minimize the climate impact of new installations.

In addition to the refrigerators and freezers required for cooling and transporting samples, screening sites may have additional energy needs for lighting, small device/mobile charging, and other appliances.

As noted above, if stand-alone solar systems are being used to power the refrigerator, these additional loads should be powered with a separate system. In the case of off-grid locations, a small solar home system (SHS) kit would likely be sufficient to meet these additional needs. Quality-verified SHS kits can be found on ***www.lightingglobal.org/products.***

The testing site, the “hub”, has much greater energy needs than the screening sites due to additional equipment required for processing samples, such as PCR thermocyclers, biosafety cabinets, air handling systems, refrigeration and freezing for reagents and samples, and others, along with conventional facility loads such as lighting, computers, and HVAC systems. Though testing sites also require reliable electricity, a description of those needs is beyond the scope of this document.

For additional guidance on the selection of refrigerators, freezers, and insulated containers, along with considerations associated with designing solar systems for vaccine refrigerators, the WHO has prepared several excellent documents that have been referenced throughout this note and are presented in the References section.

ANNEX A

Table A.1. WHO recommendations for sample storage and collection based on specimen type [1]

Specimen type	Collection materials	Storage temperature until testing in-country laboratory**	Recommended temperature for shipment according to expected shipment time
Nasopharyngeal and oropharyngeal swab	Dacron or polyester flocked swabs*	2-8°C	2-8°C if ≤5 days -70°C (dry ice) if >5 days
Bronchoalveolar lavage	Sterile container*	2-8°C	2-8°C if ≤2 days -70°C (dry ice) if >2 days
(Endo)tracheal aspirate, nasopharyngeal or nasal wash/ aspirate	Sterile container*	2-8°C	2-8°C if ≤2 days -70°C (dry ice) if >2 days
Sputum	Sterile container	2-8°C	2-8°C if ≤2 days -70°C (dry ice) if >2 days
Tissue from biopsy or autopsy including from lung	Sterile container with saline or VTM	2-8°Cw	2-8°C if ≤24 hours -70°C (dry ice) if >24 hours
Serum	Serum separator tubes (adults: collect 3-5ml whole blood)	2-8°C	2-8°C if ≤5 days -70°C (dry ice) if >5 days
Whole blood	Collection tube	2-8°C	2-8°C if ≤5 days -70°C (dry ice) if >5 days
Stool	Stool container	2-8°C	2-8°C if ≤5 days -70°C (dry ice) if >5 days
Urine	Urine collection container	2-8°C	2-8°C if ≤5 days -70°C (dry ice) if >5 days

**For transport of samples for viral detection, use viral transport medium (VTM) containing antifungal and antibiotic supplements. Avoid repeated freezing and thawing of specimens. If VTM is not available, sterile saline may be used instead (in which case, duration of sample storage at 2-8°C may be different from what is indicated above).*

***Samples may also be frozen for storage and transport.*

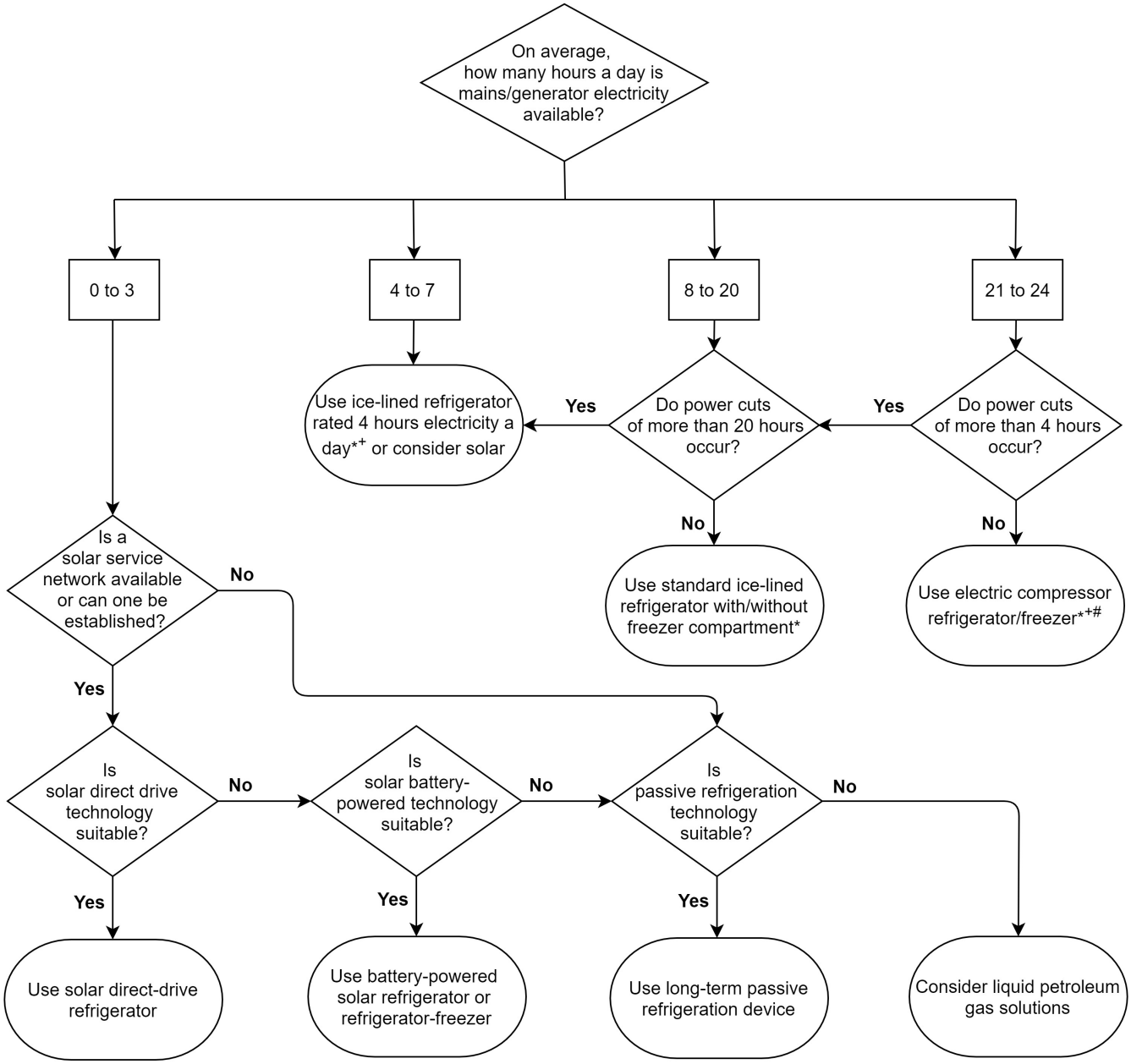
Table A.2. Common assays used in COVID-19 screening, along with their specimen refrigeration requirements [2]

Supplier	Abbott	Roche	Hologic	Cepheid	ThermoFisher
Instrument	m2000sp/rt	Cobas 6800/8800	Panther-Fusion	GeneXpert	AB 7500/7500 Fast/ Fast Dx, QuantStudio 5 RT-PCR System
Assay	RealTime SARS-CoV-2	Cobas			
SARS-CoV-2	SARS-CoV-2	Xpert Xpress SARS-CoV-2	Multiplex RT-PCR kit for detection of SARS-CoV-2		
Specimen Type	nasopharyngeal and oropharyngeal swab	nasopharyngeal and oropharyngeal swab placed in 3mL of UTM** or VTM**	nasopharyngeal and oropharyngeal placed in 3mL of VTM**	nasopharyngeal and mid-turbinate swabs and nasal wash/ aspirate in 3mL VTM**	nasopharyngeal swabs/aspirate and bronchoalveolar lavage in VTM**
Specimen Storage*	2-8°C for up to 72 hours	2-8°C and must be processed within 48 hours	2-8°C for up to 96 hours before transferred to the Panther Fusion Specimen Lysis Tube	2-8°C for up to 96 hours before transferred to the Panther Fusion Specimen Lysis Tube	2-8°C for up to 72 hours

**Specimens may be frozen to - 20°C or ideally -70°C and transported, according to WHO's guidelines, if further delays of over 72 hours are expected.*
***UTM – Universal Transport Medium; VTM – Viral Transport Medium*
****NOTE: Some reagents associated with specific assays may have their own storage/temperature requirements separate from specimens.*

ANNEX B

Figure B.1. WHO guidance on selecting a suitable device based on energy source [5]



* With voltage regulator

\+ With adequate holdover time (the time in hours during which all points in the vaccine compartment remain between +2°C and +10°C at the maximum ambinet temperature of the climate zone for which the appliance is rated, after the fuel supply has been disconnected). Refer to PQS Catalogue datasheets for holdover times of ice-lined refrigerators.

\# Do not use domestic refrigerators unless lab tested to PQS standards

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