MADAGASCAR

Integrated Energy Access Planning

COLD CHAINS REPORT

JUNE 2024

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ABBREVIATIONS

ADER	Rural Electrification Agency (Agence de Développement de l'Electrification Rurale)
AFD	Agence Française de Développement
AfDB	African Development Bank
AVC	Agricultural Value Chain
BCG	Bacille Calmette-Guerin
CaaS:	Cooling as a Service
CCE	Cold Chain Equipment
CDPHM	Distribution Center of Fishery Products of Mahajunga (Centre de Distribution des Produits Halieutiques de Mahajunga)
CEFFEL	Consulting, Experimentation and Training on Fruits and Vegetables (Conseil Expérimentation Formation en Fruits Et Légumes)
CHD	District Hospital - Centre Hospitalier de District
CHR	Referral Hospital - Centre Hospitalier de Référence
CHRD	Referral Hospital at District level - Centre Hospitalier de Référence de District
CHRR	Referral Hospital at Regional level - Centre Hospitalier de Référence de Région
CHU	University Hospital - Centre Hospitalier Universitaire
CIRAD	International Cooperation Center on Agronomy and Research (Centre de Coopération Internationale en Recherche Agronomique)
CRNM	Medical and Nutritional Rehabilitation Centre (Centre de Réadaptation Nutritionnelle et Médicale)
CSB1/CSB2	Basic Health Center (Centre de Santé de Base), level 1 and 2
DPEV	Directorate of the Expanded Immunization Programme (Direction de Programme Élargi de la Vaccination)
DPT	Combined vaccine for Diphtheria-Pertussis-Tetanus
DRSP	Regional public health directorate (Direction régional de la santé publique)
ESMAP	Energy Sector Management Assistance Program – World Bank
FDA	Agricultural Development Fund (Fonds de Développement Agricole)
IFAD	International Fund for Agricultural Development
GEAPP	Global Energy Alliance for People and Planet
GHI	Global Horizontal Irradiation – Irradiation Solaire Horizontale Globale
GIS	Geographic information system
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit – Agence coopération International allemande pour le développement
GLCEP	Geospatial Least-Cost Electrification Plan – (Plan Géospatial d'Electrification à moindre coût)
GoM	Government of Madagascar
HV	High Voltage
HFC	Healthcare Facility
IEP	Integrated Energy Access Plan
INSTAT	National Statistics Institute (Institut National de la Statistique)
IPP	Independant Power Producer

JIRAMA	Jiro sy Rano Malagasy – Electricity public utility
JSI	John Snow Inc.
LEAD	Least-Cost Electricity Access Development Project (Projet de développement de l'accès à l'électricité au moindre coût) - World Bank
LV	Low Voltage
MEDD	Ministry of Environment and Sustainable Development (Ministère de l'Environnement et du Développement Durable)
MECS	Modern Energy Cooking Services
MEH	Ministry of Energy and Hydrocarbons (Ministère de l'Energie et des Hydrocarbures)
MICC	Ministry of Industry, Trade and Consumption (Ministère de l'industrie et de la Consommation)
MINAE	Ministry of Agriculture and Livestock (Ministère de l'Agriculture et l'Elevage)
MPEB	Ministry of Fisheries and the Blue Economy (Ministère de la Pêche et de l'Economie Bleue)
MSANP	Ministry of Public Health (Ministère de la Santé Publique)
MTF	Multi Tier Framework
MV	Medium Voltage
NEP	New Energy Policy (Nouvelle Politique de l'Energie)
OPEC	Organization of Petroleum Exporting Countries
ORE	Electricity Regulatory Authority/ (Office de Régulation de l'Electricité)
OSM	Open Street Map
PHC	Powering Healthcare
PQS	Performance, quality and safety
PEV	Expanded Programme on Immunization (Programme Elargi de Vaccination)
PrAda	Agriculture Value Chain Adaptation to Climate Change Project (Projet d'Adaptation des chaînes de valeurs agricoles au changement climatique)
PV	Photovoltaic
RBF	Results Based Finance
RH	Relative Humidity
ROI	Return on Investment
SDD	Solar Direct Drive
SDG	Sustainable Development Goal
SDSP	District level service for public health (Service de District de la Santé Publique)
SEforALL	Sustainable Energy for All
SSS	Standalone Solar PV system
UCC	Ultra Cold Chain
UEF	Universal Energy Facility
UN	United Nations
UNICEF	United Nations International Children's Emergency Fund
UNIDO	United Nations Industrial Development Organization
UNDP	United Nations Development Program
USAID	United States Agency for International Development
WFP	World Food Program
WHO	World Health Organization
WUENIC	WHO/UNICEF Estimates of National Immunization Coverage

KEY TERMS

Agricultural Cold Chain: A series of refrigerated and temperature-controlled storage and transportation processes used to maintain the quality, safety and shelf-life of perishable agricultural products, such as fruits, vegetables, dairy products and meats.

Bacille Calmette-Guerin (BCG): A vaccine for tuberculosis that should be administered at birth.

Biofuels: Renewable fuels made from organic matter, such as plants and plant-derived materials.

Component: The components of the Integrated Energy Access Plan are the least-cost electrification plan, clean cooking plan, medical cold chain plan and the agricultural cold chain plan.

Cooking devices/Cooking appliances: A device and/or appliance regardless of fuel associated, e.g., "cookstove" or "pressure cooker".

Cooking fuels: Fuels used to provide heat for cooking, including wood, charcoal, kerosene, gasoline, ethanol, propane, natural gas and butane.

Cooking technologies: Potential combinations of cooking fuels and cooking appliances, e.g., "LPG cookstoves".

Densification: In many places along the existing JIRAMA network, houses and small businesses are located close to the low-voltage (LV) distribution network but are not connected. Densification refers to the process of connecting unserved houses and businesses with electricity service via short LV extensions and service connections.

Diphtheria-pertussis-tetanus (DPT): An important vaccine preventing these three diseases in children who should receive three doses before the age of one. Receiving the third dose of DPT indicates completion of the initial routine infant vaccine series.

Distribution transformers: Distribution transformers transform medium voltage (MV) power (20, 15 or 5 kV in most cases) to a lower voltage for use by residential and commercial consumers. The LV networks in Madagascar are energized at 400 volts.

Electrification project (project): The term "project" is used in this report to define an individual investment for an MV line extension longer than 500 meters to interconnect one or more transformers, and to include an LV distribution network from each transformer through which consumer connections can be made.

Fokontany: An administrative delimitation grouping together several villages that make up the commune.

Geospatial model: All spatial analysis was conducted in a geographic information system that will aggregate specific geospatial and non-geospatial data and databases to conduct analysis using geospatial models and algorithms. The phrase geospatial model refers to the geospatial analysis and data models as contained within the geographic information systems' database used for the project.

Grid extension: The process of connecting unserved houses and businesses with electricity service via extension of the MV distribution system, new distribution transformers and extension of the LV for new service connections.

High voltage (HV): High voltage is also considered transmission voltage. Most transmission networks operate at 66 kV or higher. The Madagascar Grid Code lists HV as above 50,000 volts.

Integrated Energy Access Plan (IEP): A plan that integrates the optimal approach for achieving universal energy access for electrification and cooking, while also providing options for optimal cold storage for medical and agricultural cold chains, in support of the Government of Madagascar (GoM). The IEP is also referred to as the study or plan.

Isolated grids: Existing non-interconnected national utility (JIRAMA)-operated distribution grids, which may also contain their own source of power, via renewable, thermal, hydro or other sources.

Low voltage (LV): Low voltage is the voltage level used by consumers. LV networks in Madagascar are energized at 400 volts.

Medical Cold Chain: Cold chain that is used for non-vaccine related health products such as blood, lab draws, reagents and some disease-specific tests.

Medium voltage (MV): Medium voltage is considered a distribution voltage that is used to distribute electricity from grid substations to communities or larger industrial consumers. MV levels in Madagascar include 20, 15 kV and 5 kV voltage levels.

Mini-grid: Distribution systems (either LV or MV) that are independent of electric distribution systems and rely on distributed generation resources such as solar PV, small hydro, thermal or other sources. In the context of this report three mini-grid categories are used. They are: 1) grid-edge MV mini-grids that refer to larger mini-grids that are near to JIRAMA networks; 2) isolated MV metro-grids that will provide service to population centres that are not connected to an existing network; and 3) LV mini-grids that will serve smaller population centres with isolated power systems using an LV distribution grid.

On-grid: Connected to the national interconnected electricity grid network.

Off-grid electrification: Encompassing mini-girds and standalone solar solutions for households, businesses and public institutions. These do not include grid-tied renewable energy generation systems.

Performance, quality and safety (PQS): A designation by WHO for cold chain equipment indicating it meets global standards to be used for vaccines and other medical commodities.

Power transformers: Power transformers transform HV (35 kV or higher) to MV levels – usually 20, 15 or 5 kV as an integral part of a grid substation.

Substation: A facility that includes transformers, protection and coordination equipment, switches and gantries, the purpose of which is to transform electrical power from one level of voltage to another. Grid substations transform transmission voltages (normally above 32 kV) to MV levels, usually to 20, 15 or 5 kV.

Standalone solar solutions: Standalone PV and battery systems of various sizes that provide electricity access to specific loads (household, institutions, businesses) and do not distribute electricity beyond one consumer or connection point.

Vaccine Cold Chain: Cold chain equipment (refrigerators and freezers) that are used to store vaccines at health facilities and stores (regional, communes). Can also refer to walk-in cold rooms that are larger pieces of cold chain equipment (CCE) typically at national and regional levels.

Visualization Platform (platform): An online, publicly available, interactive and user-friendly data visualization platform that equips policymakers and energy practitioners with data and insights to make informed decisions on strategies and operations to advance energy access in the country.

INTRODUCTION

Madagascar is the world's second largest island country with an area of 572,000 square kilometers and a population of approximately 29.6 million people.[1] It also has the unfortunate distinction of having one of the highest poverty rates in Southern Africa. Agriculture employs nearly 80 percent of all adults in Madagascar and accounts for almost 43 percent of GDP.[2] The primary crops include rice, cassava, potatoes and sweet potatoes. An estimated 2,600 health clinics provide immunization in Madagascar.[3]The rate of routine vaccine coverage has declined recently due to COVID-19 disruptions and is currently estimated at 51 percent for BCG and 70 percent for the first dose of DPT.[4] Low coverage numbers are more pronounced in more rural and remote areas.[5]

Electricity service is managed by JIRAMA (Jiro sy rano malagasy), the state-owned electricity and water company that operates a series of small generation-distribution service networks that serve major population centres with limited service to rural areas. The Agency for the Development of Rural Electrification (ADER) coordinates off-grid electrification planning, as several mini-grid and standalone solar distributors implement and operate over 100 mini-grid systems. The current reported electrification rate is approximately 35 percent[6] (2023, Tracking SDG7 Report) while access to clean cooking devices is far lower at just 5 percent of Malagasy households.

In light of the challenges facing Madagascar's energy, health and agricultural sectors, Sustainable Energy for All (SEforALL) and the Government of Madagascar (GoM) have agreed to sponsor and develop the Madagascar Integrated Energy Access Plan (IEP). The IEP will provide integrated electrification, clean cooking and cold chain analysis to support increased access to modern energy and associated services for urban, peri-urban and rural communities throughout Madagascar. The cold chain access plan will evaluate the means to improve refrigeration service to support vaccine storage and distribution, as well as refrigeration services for agricultural and food products. The IEP is intended to support improved energy and electrification policy development as well as to provide a public-facing point of reference for investment in energy resources for Malagasy businesses and communities to help public and private stakeholders identify optimal pathways to improved energy access and service delivery.

Madagascar IEP overview

To develop the Madagascar IEP, SEforALL engaged a consortium of experts led by NRECA International, and supported by JSI, Arizona State University, DGrid and Fraym. The consortium employed a geographic information system (GIS), model and analysis framework to integrate multiple data sources including power sector infrastructure data, population and demographic

[1] World Bank, 2022. https://data.worldbank.org/country/madagascar

[2] FIDA 2021. Programme d'options stratégiques pour le pays 2022-2026.

[3] Madagascar Vaccine Supply Chain Network Analysis, 2019, JSI.

[4] Performance de la Vaccination de Routine, Janvier 2023. Direction du Programme Elargi de Vaccination.

[5] SEforALL, Consultancy Services for Integrated Energy Planning (IEP) Madagascar, 2023.

[6] In 2020, Tracking SDG7 report (2022).

data, clean cooking data, health centre and vaccine infrastructure and programme management data and agricultural value chain data, among others. These geospatial datasets modelled – using a gender-responsive approach – electrification, clean cooking, vaccine refrigeration and agricultural cold chain solutions.

This is an ambitious project which builds upon experiences from SEforALL's recent integrated energy planning projects in Nigeria (2021) and Malawi (2022). With an apex goal of providing the GoM with high-quality evidence and geospatial plans to advance access to electrification, clean cooking and more efficient medical and agricultural cold chains, the IEP for Madagascar was undertaken to achieve the following primary objectives:

- Prepare and present a gender-sensitive integrated energy plan that synthesizes a least-cost geospatial electrification plan building upon recently completed electrification analyses undertaken in 2018 and 2021[7] to evaluate the least-cost pathway to universal electrification in Madagascar. The analysis places a particular emphasis on electrification of public facilities and opportunities to enhance productive-use potential using existing or new data on affordability analysis.

- Prepare a scenario-based geospatial clean cooking model to promote the adoption of imrpoved and modern energy cooking services throughout Madagascar. This analysis includes substitution of improved cooking devices, alternative biomass fuels or electricity for traditional cooking fuels. The integrated electrification and clean cooking analyses are prepared on a single geospatial information system using common attribute layers to evaluate technology options and total ownership costs of alternative technologies. This analysis covers both household and institutional cooking as part of the project scope.

- Develop a geospatial modelling framework that allows analysis of logistical costs, constraints and challenges for both medical and agricultural cold chains. The analysis incorporates medical cold chains for routine vaccinations, COVID-19 vaccinations and future vaccination needs. Additional analysis of agricultural cold chains includes an assessment of the categorization, volume, energy demand and total cooling cost of various agricultural products including sensitive crops, fisheries, dairy, meat and other temperature-sensitive produce or agricultural products. These cold chain analyses are then incorporated into the electrification and cooking models to identify areas where additional energy access priorities may arise within Madagascar for equitable access to cooling and refrigeration.

- Ensure that all public and private stakeholders can readily access and use IEP models and results including primary and secondary data. To achieve this goal, this project includes capacity building provided at multiple intervals during project implementation, including capacity building targetting women to ensure their equitable access and use of the data, as well as data management coordination particularly leading up to transfer of the database and models to the GoM.

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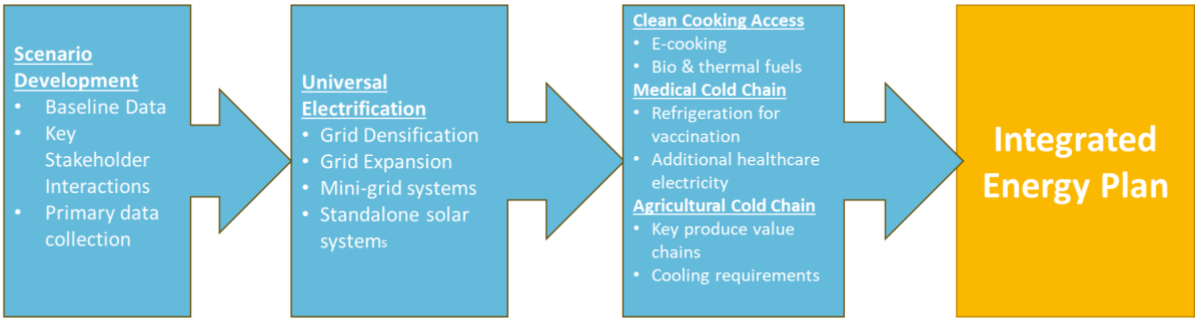
[7] Assistance Technique a la Préparation d'une analyse des options d'électrification géospatiale au moindre cout pour un déploiement sur réseau et hors réseau Madagascar, Rapport Finale. World Bank, August 2021.

- Develop a publicly available visualization platform designed to provide access to all data layers, results and scenario analysis for stakeholders for which these analyses were intended. The visualization platform is designed for ease of use to allow stakeholders to access, interact, download and analyze the data and tools in a user-friendly manner, and the platform will be available to the public.

The IEP presents an integrated analysis of inter-related electrification, clean cooking, vaccine distribution and agricultural cold chain solutions into an holistic energy plan. The electrification model is designed to integrate clean cooking and cold chain analyses with rural and peri-urban electricity demand. Scenario and sensitivity analyses are prepared for electrification, clean cooking and cooling infrastructure. These analyses are used in concert with one another to present comprehensive projections of electrification, clean cooking, vaccine distribution and agricultural cold chain expansion for Madagascar's energy future.

Figure 1. Organigramme de l'élaboration du PEI.



Purpose of this report

This report presents the cold chain component of the Madagascar Integrated Energy Plan (IEP). The cold chain component incorporates two distinct sub-components – first the medical cold chain and then the agricultural cold chain, which are presented in series. Within each subcomponent's section, an overview and brief gap analysis is presented, followed by a section summarizing the field data collection and validation completed during the project. From there, the methodological approach to the cold chain analysis is presented, followed by the results of the cold chain modelling, sensitivity analyses and final cooling energy and cost requirements. A final section on key conclusions and recommendations is presented at the end of the document.

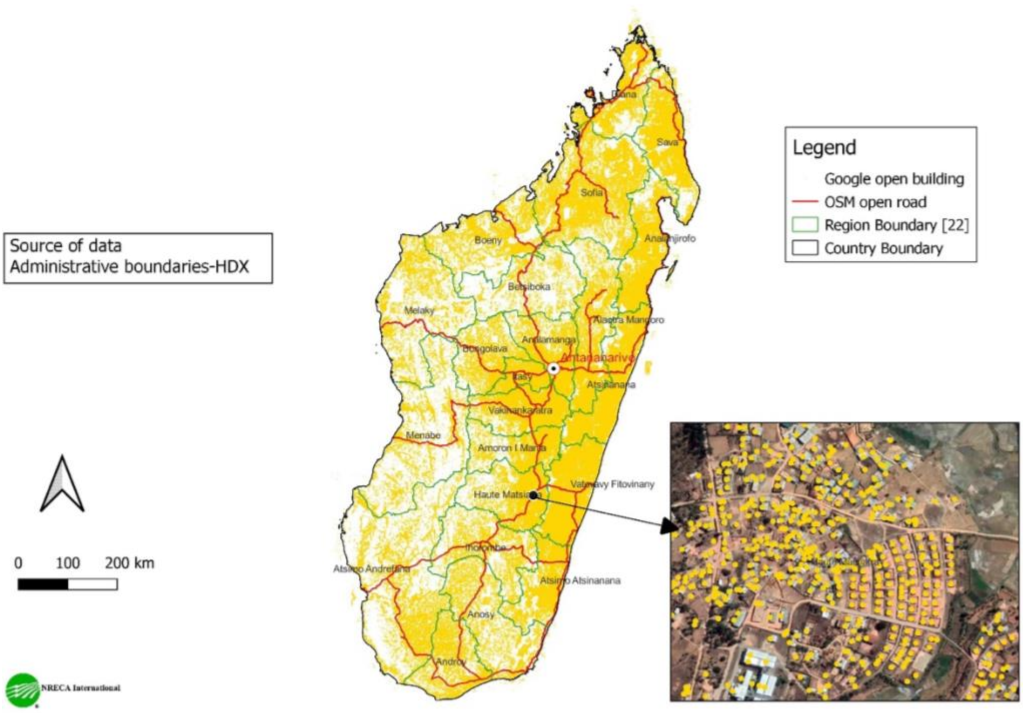
Cold Chain Challenge in Madagascar

The cold chains in Madagascar face two significant challenges: limited electricity access and insufficiently developed road infrastructure. In areas where electricity is unreliable or non-existent, maintaining the required temperature for vaccines and/or agricultural produce becomes nearly impossible. Furthermore, inadequate road networks can hinder the timely transportation of temperature-sensitive products from farms to markets or for vaccines from regional warehouses to rural clinics. Throughout Madagascar, seasonal precipitation, insufficient infrastructure, low purchasing power and lack of innovation (due to lack of knowledge on the part of users, especially small-scale producers) and difficult terrain make it challenging to ensure cold chain integrity.

Addressing electricity access and road infrastructure issues are crucial to enhance food security and reduce post-harvest losses as well as ensure availability of vaccines at health facilities and accessibility for all people. The electricity access challenge is discussed in greater detail in the Madagascar IEP electrification report, while many of the challenges discussed in this report both in terms of medical and agricultural cold chain constraints arise from the limited vehicular accessibility within the country, which is explored in more detail below.

In many cases, cold chain interventions are necessary due to extended travel time between central vaccine storage facilities and remote clinics or from remote agricultural production sites and markets. In preparing the geospatial models for the cold chain report, a complete geospatial database of all structures and roads in Madagascar was compiled to analyze the transportation of vaccines and agricultural goods within the country. This map is presented in Figure 2, using buildings data from Google Open Buildings and roads from Open Street Map (OSM).

Figure 2. Database of structures and primary roads in Madagascar
(Source: Google, OSM)



With such a large country and significant changes in terrain, rainfall and population density, the vehicular accessibility challenge arises from several factors including seasonal precipitation, potential banditry and insufficient infrastructure. The seasonal rains can damage common roadways and greatly increase hazards to motorists and communities in floodplains surrounding roadways. Local communities have become accustomed to these periodic flood events and in some regions, they cope with inaccessibility by instituting ferry systems or even fording the waterways in 4x4 vehicles. Similar challenges befall both the medical and agricultural cold chain for delivery of vaccines and agricultural goods and products. Some examples of these vehicular hazards are presented in Figures 3 and 4. Figure 3 is a vehicular ferry about to disembark at Bekopaka in the Melaky region. Figure 4 shows high water during the dry season interfering with a roadway between Antsalova and Bekopaka. Local medical personnel have confirmed that the roadway is impassable during the rainy season. Therefore, medical practitioners have developed a complex system for equipping clinics with vaccines during the rainy season. It is necessary to hire a team to walk for one week each way with a cold-box vaccine cooler that can then be transported across the river via canoe.

Figure 3. A seasonal ferry crossing in Madagascar
(Source: JSI, 2018)

Figure 4. A seasonal road ford crossing in Madagascar
(Source: JSI, 2018)

The resourceful measures employed by medical practitioners do not work for all vehicles and may not work in all seasons. Thus, until more comprehensive transportation infrastructure can be established in remote regions of Madagascar, and the challenge of banditry can be comprehensively addressed, there will remain accessibility challenges that constrain the agricultural and medical cold chain solutions. Simply having universal access to electricity, for example may not prevent food or vaccine spoilage, if the materials are unable to reach markets for sale or clinics for vaccination.

As a result of these observations, a map is presented in Figure 5 that illustrates accessibility challenges in Madagascar by comparing the number of months in which roadways are passable. The underlying data in Figure 5 were provided by the Malagasy Ministry of Health (MoH) from a dataset of 2,284 basic healthcare centres in 2014. Today's MoH health facility dataset comprises 2,832 CSBs, but the overall trend is believed to be illustrative of present-day access challenges. Figure 6 provides the analysis of road conditions per the 2017/2018 World Bank Measuring Rural Access Report.

Figure 5. Seasonal road accessibility in Madagascar (Source: JSI 2014)

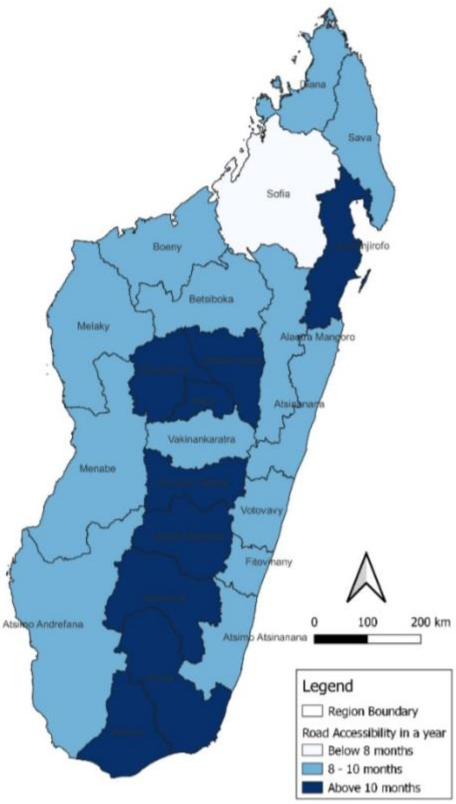
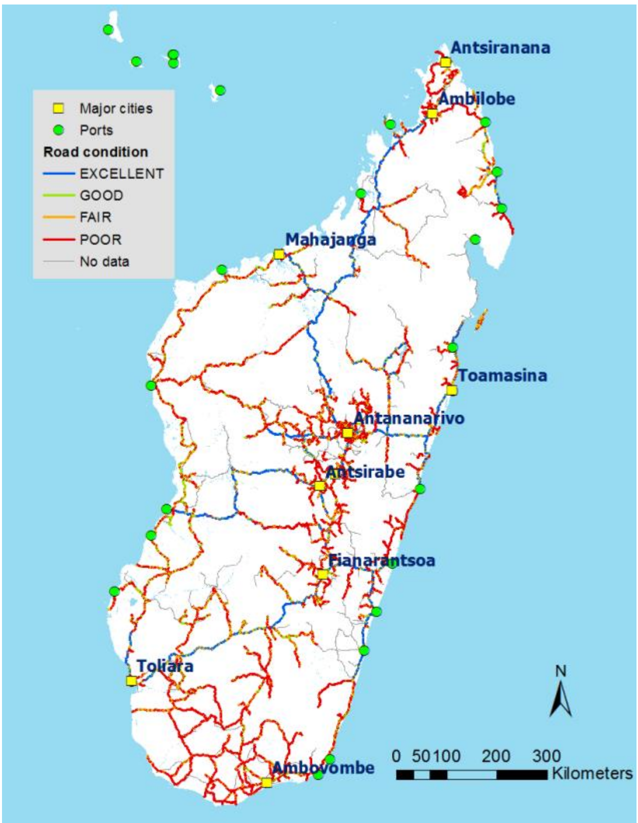


Figure 6. 2017 data on road conditions (Source: World Bank 2017)



MEDICAL COLD CHAIN

Overview

The objective of this medical cold chain component of the Integrated Energy Plan (IEP) is to conduct a comprehensive assessment of the overall immunization programme and the associated medical cold chain in Madagascar. This assessment encompasses the COVID-19 vaccine introduction and distribution efforts undertaken in the past two years, while meticulously mapping the supply chain, leveraging health centre location and facility data, road network information, cold chain technology options and the energy supply necessary to sustainably power the cold chain solutions.

This multifaceted analysis serves a threefold purpose. Firstly, it aims to enhance the efficiency and reliability of the existing supply chain. Secondly, it is instrumental in preparing the country for the ongoing expansion of the immunization programme, including the achievement of new targets related to COVID-19 vaccines and potential future vaccines, such as those for malaria. Lastly, the data gathered will be instrumental in identifying additional energy requirements essential for supporting vaccine distribution and storage nationwide. Moreover, it will facilitate an in-depth examination of various delivery scenarios to determine the most effective means of reinforcing the existing cold chain system.

Medical cold chains are required for vaccines to ensure their quality. Cold chains are important to ensuring the availability of vaccines at healthcare facilities and accessibility for all people, mainly children, who are eligible for vaccines. In Madagascar, routine vaccines are provided at designated healthcare facilities. During outreach efforts, mobile health teams travel to communities in remote areas and those with difficult access to ensure vaccines are made available. The coverage rate for routine vaccines has declined in the past several years due to COVID-19 disruptions in vaccine supply chains and healthcare access. In 2023, the Ministry of Health (MoH) immunization programme prioritized vaccination of "zero-dose" children, defined as those who have not received the first dose of the diphtheria-pertussis-tetanus (DPT) vaccine. Based on recent administrative data, the estimated coverage rate for all vaccines varies between 51 percent for Bacille Calmette-Guerin (BCG) and 70 percent for the first dose of DPT. Regionally, low coverage numbers are more pronounced in more rural and harder-to-reach areas.

Over the past two years, the immunization programme has also conducted large-scale campaigns for the COVID-19 vaccine, integrating it into the vaccine cold chain using the same equipment as traditional vaccines. The Covishield COVID-19 vaccine was introduced in May 2021, and 8,728,396 doses of the vaccine had been administered by June 2023. This represents 17.4 percent coverage or 2.6 million people fully vaccinated (an estimated 450,000 people received a first dose and are still awaiting a second dose to be considered fully vaccinated), falling short of the government's target of reaching 50.5 percent of Madagascar's population.[8] Efforts in 2023 were focused on integrating the COVID-19 vaccination programme into routine service delivery, with a focus on

[8] Ministère de la Santé. Plan National de Déploiement et de Vaccination (PNDV) contre la Covid-19 à Madagascar. Septembre 2021.

mature adults and high-risk populations, as per the most recent World Health Organization (WHO) recommendations.

Vaccines arrive in Antananarivo directly from the manufacturer based on a supply plan in coordination with UNICEF, the main procurement agent for the country, and the plan is adjusted based on need and cold chain equipment (CCE) capacity. The country is in the process of constructing a new walk-in cold storage facility at the international airport to alleviate the constraint at the national level, as well as to facilitate arrivals and ensure cold chain reliability. An additional 373 pieces of equipment are also being procured for district and facility levels. According to MoH policy, vaccines are delivered from the central-level warehouse directly to the district stores on a quarterly basis, bypassing the regional level of the health system. According to the immunization supply chain team and supply planning tools, health facilities collect vaccines from district stores monthly, and normally keep a buffer stock of approximately two weeks, though there is no official policy on buffer stock. (Table 1). While this is the MoH policy, the practice is changed as necessary by the vaccine distribution team, particularly to accommodate the rainy season, which creates accessibility issues in hard-to-reach facilities, in some locations cutting off health centres from reliable transport to their district resupply point for several months at a time. There is no vaccine storage at the region or commune levels.

Known On-Going Projects Related to CCE and Electrification

- Least-Cost Electricity Access Development (LEAD) Electrification: A World Bank project that provides improved access to electricity services for households, enterprises and healthcare facilities in Madagascar. As of August 2023, 47 healthcare facilities had been electrified with plans to complete 453 more.
- On-going installation of walk-in cold room at national level for vaccine storage with GAVI support.
- 29 new pieces of CCE are currently in the country and waiting to be installed (purchased by UNICEF and the World Bank's MIAROVA project); installation should be completed by the end of 2023.
- The country is currently purchasing:
    - 373 CCEs through GAVI, which should arrive and be installed in 2024 (Cold Chain Equipment Optimization Project CCEOP2).
    - 100 solar refrigerators (GAVI/CDS3) 2024.
    - 115 electric freezers with solar kits (World Bank's Miarova project) 2024.

Figure 7 maps the healthcare facilities in Madagascar by type, while Figure 8 provides an overview of the location of the LEAD-supported healthcare facilities. Further analysis on healthcare facility electrification is found in the IEP Electrification Report.

Figure 7. Healthcare facilities by type in Madagascar (2023)

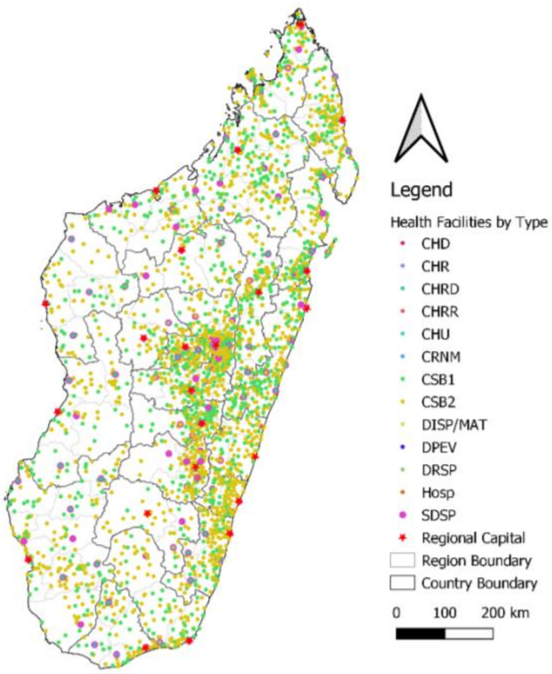


Figure 8. LEAD supported healthcare facilities in Madagascar (2023)

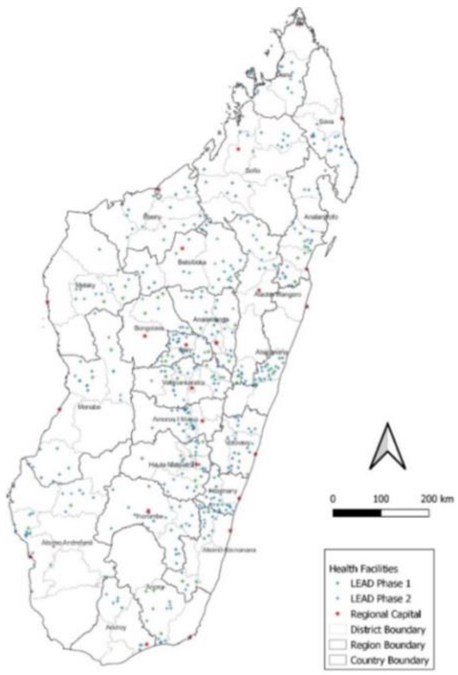


Table 1. Supply chain levels and distribution practices

Supply Chain Level	Distribution Method: Routine and COVID-19 vaccines
National level	Stores vaccines, makes decisions about quantities to distribute Has 5 trucks including 2 refrigerated trucks (note: only 1 truck was currently working as of September 2023) to distribute vaccines quarterly to district level. UNICEF provides additional transport when needed. Vaccines are stored in cold boxes during distribution if a cold truck is not available.
Regional level	Administrative only; not used to store vaccines.
District level	Receives vaccines quarterly from national level.
Healthcare facility level	Collects vaccines from district level on a monthly basis using a variety of transportation methods (government motorcycles, public transport, boat, zebu carriage, or on foot).
Commune	Healthcare facility staff use bicycles or motorcycles with a small cooler for a day of service provision 5–10 km away from the facility.

Note: The COVID-19 vaccine has been integrated into the routine vaccine supply chain and cold chain, using the same cold chain equipment and transport. The country has 6 ultra-cold chain equipment specifically for the Pfizer vaccine located at national and district levels.

Methodology Summary

The Expanded Programme on Immunization (EPI) of the Ministry of Health (MoH), the Rural Electrificstion Agency (ADER) and the MoH Planning Department collaborated to collect the multiple datasets related to health facilities, characteristics, locations and services provided. An important document for the medical cold chain analysis was the cold chain equipment (CCE) inventory provided by EPI, which was updated at the end of 2022. This inventory provides insight into CCE that is used for storing vaccines and has implications for electricity use, particularly in the case of solar CCE. Information available in this secondary data was confirmed and clarified through EPI stakeholders.

Data Collection and Validation

Based on close collaboration with the MoH, EPI, UNICEF and ADER, the study team was able to obtain data sources, cross-check sources, validate assumptions and clean the data. This process resulted in a central facility list that was agreed upon (by the IEP cold chain stakeholders) and that combined multiple data sets – see Table 2.

Table 2. Key data points collected for analysis and the source of the data sets

Data	Source	Granularity	Date Updated or Received
Healthcare facility names and types	MoH	Facility level (regional, district, facility)	MoH/DPEV (updated Nov 2022); MoH/DSSB (updated June 2023)
Healthcare facility GIS coordinates	ADER, LEAD	Facility level (regional, district, facility)	ADER (received April 2023); LEAD (received July 2023)
Health facility energy availability	MoH	Facility level (regional, district, facility)	MoH/DPEV (updated Nov 2022)
Population/ catchment data	MoH Planning Department	Facility level (regional, district, facility)	MoH/DPEV (updated Nov 2022)
Cold chain equipment (CCE) assets, functional status, characteristics	EPI inventory (updated November 2022), WHO PQS catalogue	Facility level (regional, district, facility)	MoH/DPEV (updated Nov 2022)
Vaccine item dimensions	MoH, WHO prequalified list, measurement at warehouse (Rotavirus)	By type of vaccine, by SKU (Rotavirus)	MoH/DPEV (updated Nov 2022); WHO (accessed July 2023); DPEV warehouse (measurement taken July 2023)
Routine immunization schedule	EPI	National level	MoH/DPEV (updated Nov 2022)
COVID-19 vaccine rollout updates	EPI	District	MoH/DPEV (updated July 2023)
Supply chain and distribution policy	EPI	Facility level (regional, district, facility)	MoH (discussions, 2023)
Fokontany GIS coordinates and characteristics	ADER	Fokontany level	ADER (received April 2023);
List of facilities with LEAD support and planned LEAD support	LEAD	Facility level	LEAD (received July 2023)

These datasets were then harmonized, ensuring consistency across the multiple datasets of healthcare facilities, particularly with how the facility names are written. Geographic coordinates were available for most facilities, although missing for district-level vaccine stores. Geographic coordinates were assigned to every facility (3,053 total facilities) based on the following assumptions:

- 497 facilities included in the LEAD electrification use the facility's coordinates per the LEAD files (three are missing because they had latitude twice, rather than latitude and longitude, in those files. Among the three missing, two are identified by fokontany, and one by commune, see below).
- 1,674 facilities use the fokontany's GPS coordinates. This matches the region, district, commune and fokontany name (derived from the facility name) to match to the associated fokontany in the fokontany GIS file from ADER.
- 850 facilities where it was not possible to find a direct match based on the fokontany, use an estimation based on the commune – this is an average of the GPS coordinates of all the fokontany listed in that commune in the fokontany GIS file from ADER.
- Finally, there are 32 facilities unidentifiable by commune or fokontany (or they were unclear because there were multiple fokontany of the same name in different communes within the same district); these were incorporated in the model by using an estimation based on the district, which is an average of the GPS coordinates of all the fokontanys in the district.

Analysis of CCE looked at its age, the number of manufacturers and models, which has implications for maintenance, and at performance, quality and safety (PQS) standards.[9] The analysis also considered the CCE on- and off-grid and the implications for the IEP.

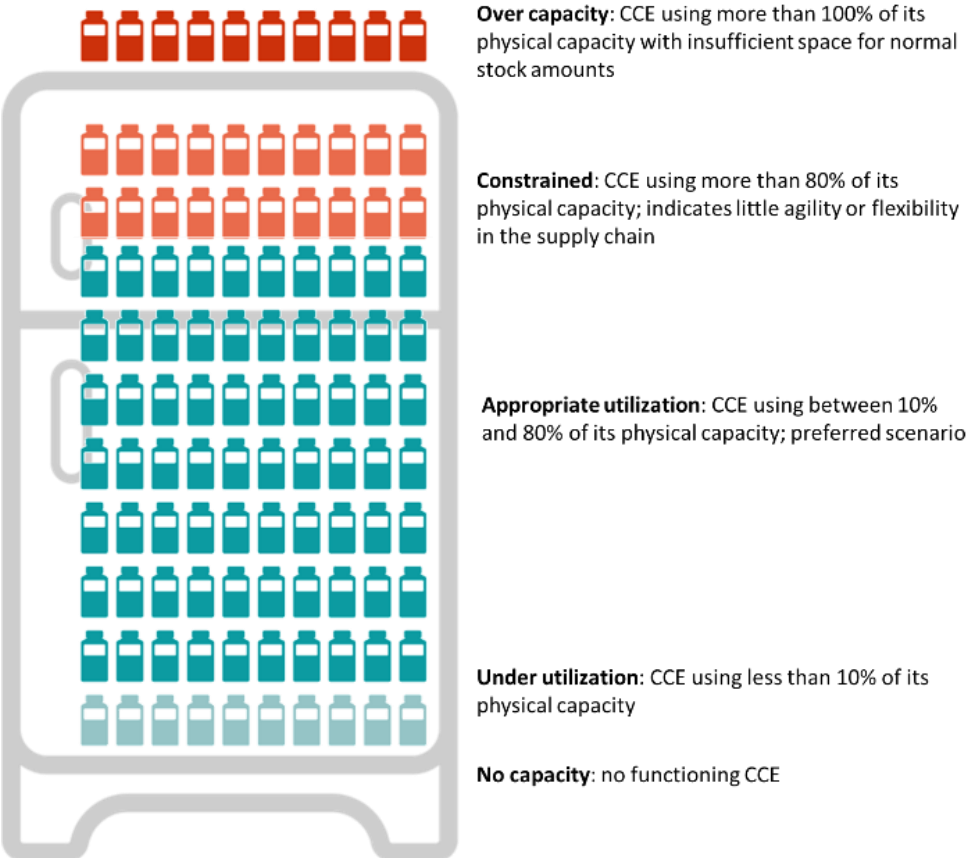
Additionally, the IEP conducted a capacity utilization analysis for the CCE at the healthcare facilities and storage sites to indicate the level of utilization and particularly if any sites had constrained capacity and needed either additional CCE or different vaccine distribution frequency. Capacity utilization is estimated using the vaccine quantity required based on the EPI schedule (e.g., vaccines and number of doses required of each); stated distribution schedule (e.g., monthly distribution to facility level and quarterly to district); target population of each facility and district; and vaccine characteristics (vial size, cubic liters per dose, wastage rate, buffer stock). This is assessed against the total net cubic liters of the PQS-approved CCE available and functioning at the facility and used for vaccines. Utilization categories are defined as:

- Appropriate if between 10 percent and 80 percent of physical capacity is used
- Underutilized if less than 10 percent of capacity is used
- Constrained if more than 80 percent of capacity is used
- Over capacity if more than 100 percent is used or
- No capacity to indicate that no functioning CCE is available.

[9] WHO's Performance, Quality and Safety process prequalifies products and devices so that governments are assured of their suitability for use in immunization programmes; it also establishes energy efficiency standards.

Appropriate capacity use is considered ideal. For the COVID-19 vaccine, there is no standard policy currently in place for distribution and storage requirements. As such, the quantity of the COVID-19 vaccine that is distributed to a facility level largely depends on the availability of the vaccine and is not necessarily based on the target population. This complicates a definitive analysis of the capacity utilization; however, with the majority of CCE in healthcare facilities using less than 10 percent of their physical capacity, the analysis indicates the capacity is sufficient to accommodate an appropriate quantity of the COVID-19 vaccine relative to the target population. Additional influencers are the low interest in receiving the vaccine as the pandemic has moved to an endemic stage, as well as the smaller quantities of COVID-19 vaccines being donated to the country.

Figure 9. Visualization of the capacity utilization categories



There were some limitations to the methodology. There is no singular master dataset of facilities in Madagascar; instead, one was created from a combination of different datasets from different sources. Information was variable across the multiple data sources, with sometimes conflicting information. For example, the final dataset used includes a compilation of several different facility lists, which sometimes differed in the facilities they contained (i.e. facility X exists in list A but not list B, while facility Y exists only in B), as well as the attributes of the facilities themselves (i.e. facility X in one list is at the basic health centre (CSB)1 level, while a facility of the same name exists in another list but is referenced as being a CSB2 level). Additionally, spelling in Madagascar is often phonetic, and many places go by both an old colonial designation in French (that can differ across lists in the use of accent marks) as well as a newer Malagasy name. For example, the district now known as Boriziny appears variously across facility lists as Boriziny, Port Bergé, Port Berge, Port-Berge, Boriziny (Port Berge) and Port Berge (Boriziny-Vaovao). Cardinal directions are also used variously in both French and Malagasy across and within datasets (.e. Fenoarivo Atsinanana, Fénérive Est, Fenoarivo Est). Different datasets also differed in facility attributes such as the number of functional solar refrigerators available; in such cases, the analysis defaults to using the master cold chain list from the Directorate of the Expanded Immunization Programme (DPEV). Missing data points, especially related to geo coordinates, were filled in with assumptions based on best available information as to the location.

Scenario Development for Medical Cold Chains

Medical cold chains and healthcare facility electrification are closely linked. As such, the Integrated Energy Plan (IEP) medical cold chain analysis includes two parts: a cold chain equipment (CCE) assessment, and renewables-based electrification and/or back-up of healthcare facilities, including cold chain and non-cold chain loads. The Government of Madagascar (GoM) has an existing plan to electrify all public healthcare facilities by 2030 in line with the 2015–2030 National Energy Policy (NEP) and Ministry of Health (MoH) targets. With that in mind, only one full scenario for cold chain equipment (CCE) and healthcare facility electrification was developed for the IEP and sensitivities to the main scenario are used to illustrate the alternative options for CCE deployment.

Sustainable Energy for All (SEforALL) SDG7 Baseline Scenario:

- **Healthcare facility electrification:** Aligned with GoM targets and the baseline IEP electrification scenario, all healthcare facilities are electrified by 2030, with facility-scale solar and battery storage or solar backup systems for grid or medium voltage (MV) mini-grid connected facilities. All electrification is assumed to be 100 percent renewables based and sized to cover full mandatory equipment roster of the facility.
- **Cold chain equipment deployment:** The baseline scenario assumes that electric and solar direct-drive CCE will be deployed to fully meet the current vaccine cold chain requirements, accommodate population growth through 2030 and replace equipment that is non-functioning, non-performance, quality, standard (PQS), or has reached the end of its useful lifespan. This scenario conservatively assumes that solar direct-drive (SDD) equipment is procured for all healthcare facilities that reported less than 16 hours of electricity per day in 2023 regardless of their current or planned electrification modality, assuming that these facilities could progressively adopt electric CCE once they have been fully electrified, with the switch likely occurring beyond the 2030-time horizon.[10]

Sensitivity – Cold chain equipment procurement optimization

- **Healthcare facility electrification:** Same as the Sustainable Energy for All (SEforALL) SDG7 baseline scenario.
- **Cold chain equipment deployment:** This sensitivity examines the potential cost savings that would result from increased Coordination between CCE procurement decisions and healthcare facility electrification. It assumes that at a national level 40 percent* of the

[10] A second scenario was developed that evaluated only the cold chain equipment requirements being electrified by 2030 targets, this is available in the Annex.

procurements attributed to SDD units in the baseline scenario can instead be procured as less-expensive performant electric CCE, as these procurements will occur in facilities that have been sufficiently electrified through planned healthcare facility electrification and/or back-up schemes.

Parameters used to design medical cold chain requirements[11]

The sector is divided into four facility sizes. These sizes are based on and adapted from the USAID publication, *Powering Health: Electrification Options for Rural Health Centers*,[12] which originally specified four healthcare facility sizes that have now been narrowed them down to three. For this report's purposes, four facility sizes are used. The USAID publication specifies equipment needs for different size categories, and MoH facility types have been assigned to the USAID sizing categories in this report according to their expected equipment needs (see Table 3). The assumption is that although specific facility design requirements may differ, on average the sizing buckets will reflect the needs of the facility types.

Each facility size category is assigned an equipment roster, together with hours of demand and power consumption for each piece. Total energy demand is ascertained from the roster and summation of the aggregate energy consumption for each facility. For facilities with 24-hour grid power, solar hybrid systems were evaluated to account for grid irregularity and power quality issues. However, even intermittent grid access may be sufficient to replace backup generators needed for standalone facilities in rural areas not connected to a distribution network (JIRAMA or other). Based on feedback from local stakeholders, certain grid-connected healthcare facilities have 16–24 hours of grid service per day, whereas others have 8–16 hours of grid service per day. Therefore, solar sizing calculations for hybridization of healthcare facilities are based on the more conservative estimate of 8–16 hours of grid access. A summary of results is presented in the sections below.

Table 3. Facility types considered in the IEP analysis

Size	Name of Facility Type	Description	Energy end-use requirements
1	**Basic Health Centre (CSB1) Level 1**	Basic healthcare facilities in the Madagascan countryside. They are the first port of call for the sick. Only rarely is a doctor available on site.	They are typically off-grid, and do not necessarily have CCE, though some do. They do not typically have lighting or any other electricity available. The equipment lists for these sites include a vaccine refrigerator, general light, exam light, microscope and radio.
1	**CSB level 2 / Dispensary / Maternity**	CSB2s are slightly higher-level facilities (in less rural locations) than CSB1 and offer additional services. They are typically off-grid, but some are on-grid. They have CCE for routine vaccines, and often	They are typically also off-grid, but some are on-grid. They have CCE for routine vaccines. Same energy requirements as CSB1, plus a prenatal care scale.

[11] Please note that The Madagascar Powering Healthcare Roadmap is currently being developed by SEforALL in partnership with GoM and provides precise healthcare facility electrification sizing methodology, equipment rosters, consumption estimates and costs based on an in-depth analysis of needs and opportunities in CSBs and CHRDs.
[12] Powering Health: Electrification Options for Rural Health Centers, USAID, https://www.usaid.gov/sites/default/files/2022-05/Powering-Health_Load-Calculation-Examples.pdf

		have lighting at least some of the time.	
2	**District Hospital (CHD) / Referral Hospital at the District level (CHRD)**	The district level of care consists of two types of hospitals that provide their surrounding populations with both outpatient and inpatient services.	Services provided include maternity, emergencies, pharmacy, paediatrics, operating room, surgery, radiology, laboratory, ultrasound, dentistry. Additional energy requirements other than lighting and cold chain may include an oxygen concentrator, a suction machine, an incubator, a nebulizer, a resuscitation machine, autoclave and basic laboratory equipment such as a microscope and a haematology mixer.
2	**District-level Health Office (SDSP)**	SDSPs are typically on-grid and located in cities.	SDSPs have CCE to store the vaccines for use in the whole district; some of the cold chain storage equipment may be shared with (located at) a local district-level hospital in the same city.
3	**Referral Hospital (CHR) / Referral Hospital at the Regional Level (CHRR) / Regional Public Health Directorate (DRSP) Regional Nutrition and Maternity Centre (CRNM) -**	These facilities provide more advanced care and additional services compared to the district hospitals.	Services provided include surgery, maternity, operating room, radiology, pneumology, cardiology, dermatology, emergencies, traumatology, gastroenterology, urology, pharmacy, paediatrics, burn department.
4	**University Hospital (CHU)**	The tertiary level consists of central hospitals. They ideally provide specialist health services at the regional level and referral services to district hospitals in their region. In practice, however, around 70% of the services they provide are either primary or secondary services due to lack of a gate-keeping system. .	Energy requirements to be provided include those for surgery, maternity, family planning, vaccinations, operating rooms, immunology, radiology, neurology, pneumology, cardiology, odontology, dermatology, emergencies, traumatology, endocrinology, anatomy-pathology, haematology, gastroenterology, urology, pharmacy, maternity, paediatrics, burn department.
4	**Division of the Expanded Programme of Vaccination (DPEV)**	The central-level vaccine storage in Antananarivo at their health offices and vaccine warehouse.	The energy requirement is for several walk-in cold rooms and walk-in freezers. Feeds vaccines to all the districts of the country.

**Note: there is no regional-level vaccine warehousing.

Parameters for Medical Cold Chain Cost Analysis

Method for Determining Energy Requirements in Different Health Facility Sizes

The USAID report, *Powering Health, Electrification Options for Rural Health Centers,*[13] offers indicative equipment lists for different facility sizes that are identified.[14] The power consumption of each appliance plus indicative daily usage time is also delineated. Note, however, that the least-

[13] See - https://www.usaid.gov/sites/default/files/2022-05/Powering-Health_Load-Calculation-Examples.pdf

[14] Note that these equipment estimates are placeholder values while the Madagascar Power Healthcare roadmap is still under development.

cost electricity access development (LEAD) studies of basic health centres level 1 and 2 (CSB1 and CSB2) found larger power demand levels, particularly at the CSB2 level.[15]. In the interest of presenting indicated equipment based on a unified assumption, this report uses the USAID Powering Health facilities equipment lists and energy demands. Table 4 provides a summary of the indicated equipment lists, while a complete list of equipment sizing per facility type is provided in the Annex.

Table 4. Indicated equipment list per facility type (Source: USAID Powering Health 2023)

EQUIPMENT	QUANTITY CSB/DIS /MAT Size 1	QUANTITY CHD/SDSP Size 2	QUANTITY CHR/DRSP/CRNM Size 3	QUANTITY CHU/DPEV Size 4	UNIT POWER (Watts)
Lighting	1 ea.	40 ea.	120 ea.	120 ea.	10.0 W
Exam Light	1 ea.	2 ea.	4 ea.	8 ea.	20.0 W
Microscope	1 ea.	3 ea.	5 ea.	5 ea.	10.0 W
Radio	1 ea.	1 ea.	1 ea.	1 ea.	30.0 W
Small Refrigerator for vaccine storage	1 ea.	0 ea.	0 ea.	0 ea.	60.0 W
Large Refrigerator for Vaccine Storage		1 ea.	3 ea.	3 ea.	500.0 W
Autoclave		1 ea.	1 ea.	2 ea.	630.0 W
Fan		8 ea.	20 ea.	20 ea.	80.0 W
Rotator/Mixer		1 ea.	2 ea.	2 ea.	60.0 W
Water Bath		1 ea.	2 ea.	2 ea.	400.0 W
Spectrophotometer		1 ea.	2 ea.	2 ea.	63.0 W
Dental Chair		1 ea.	2 ea.	2 ea.	710.0 W
Compressor		1 ea.	2 ea.	2 ea.	370.0 W
Centrifuge		1 ea.	1 ea.	1 ea.	600.0 W
Jet Sonic Cleaner		1 ea.	1 ea.	1 ea.	45.0 W
Computer		2 ea.	4 ea.	4 ea.	120.0 W
Cell Phone Charger		5 ea.	10 ea.	20 ea.	5.0 W
Amalgam Filling Machine		1 ea.	1 ea.	1 ea.	80.0 W
X-ray machine			1 ea.	1 ea.	200.0 W
CD4 counters			1 ea.	2 ea.	200.0 W
Blood chemical analyzer			1 ea.	1 ea.	45.0 W

[15] See - LEAD file 47_CSB_Coordonates.pdf

EQUIPMENT	QUANTITY CSB/DIS /MAT Size 1	QUANTITY CHD/SDSP Size 2	QUANTITY CHR/DRSP/CRNM Size 3	QUANTITY CHU/DPEV Size 4	UNIT POWER (Watts)
Haematology mixer			1 ea.	1 ea.	230.0 W
Air-conditioning unit			3 ea.	3 ea.	1500.0 W
Resuscitation machine				1 ea.	165.0 W
Incubator				1 ea.	917.5 W
Prenatal Care Scale				1 ea.	2.0 W
Nebulizer				1 ea.	85.0 W
Oxygen Concentrator				1 ea.	285.0 W
Suction Machine				1 ea.	145.0 W

Using the indicate list of equipment per healthcare facility type, Table 5 shows the grouping of health facilities into energy consumption buckets, showing the electricity solution requirements, along with total facility electricity consumption in kWh per day, as well as the share of electricity consumption expected to be consumed by the cold chain equipment (CCE) at each facility. Based on the number of kilowatt-hours of expected energy consumption for each facility category determined above, standalone solar system design was performed according to conventional design practices. Note that the system designs include a 30 percent allowance for panel degradation and system Ohmic power loss as a safety margin. As such Table 5 presents the total electricity consumption in kWh/day, whereas Table 5 presents the system design size in kWh/day.

Table 5. Electricity consumption by health facility category

	Size 1 CSB/DIS/MAT	Size 2 CHD/SDSP	Size 3 CHR/DRSP/CRNM	Size 4 CHU/DPEV
Total Facility Electricity Consumption[16] (kWh/day)	0.88	18.85	85.44	93.62
Share of electricity consumed by CCE (%)	54.5%	21.2%	14.0%	12.8%
Electricity consumed by CCE only (kWh/day)	0.48	4.0	12.0	12.0

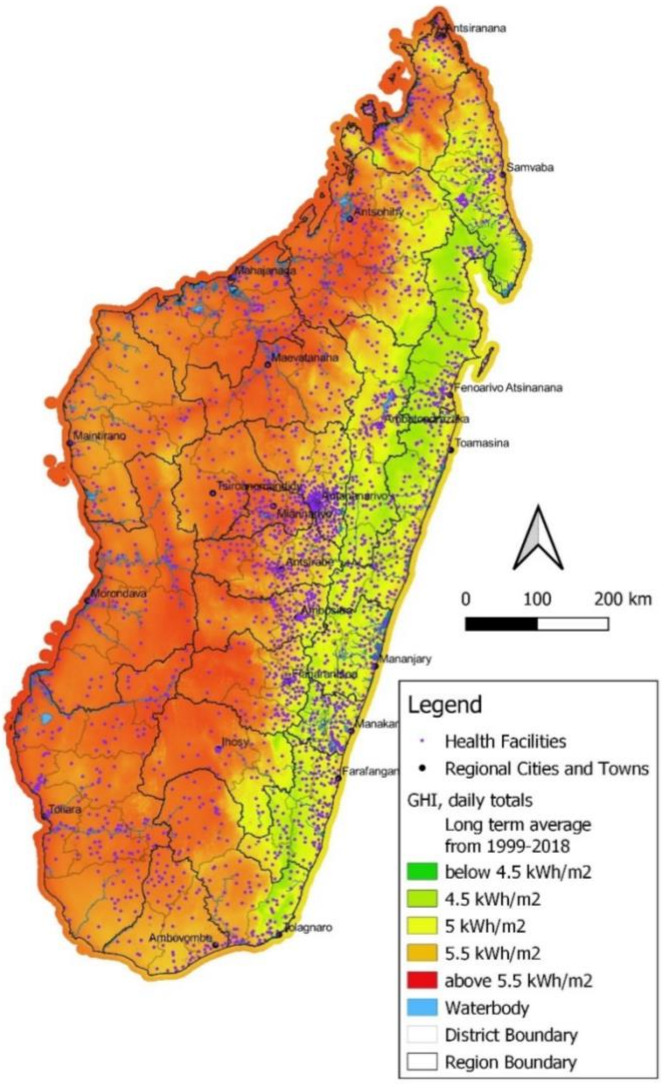
Method for Determining Cost of Energy Systems Required by Different Healthcare Facility Sizes

Actual system sizing and pricing is based on current solar module, inverter and charging equipment, battery prices and estimated cost of labour in Africa. Systems in the analysis use a current module price of approximately USD 0.44/Watt (for 550W, 72-cell panels), though large-

[16] Note that this facility electricity consumption does not take into account the panel degradation or system losses that are accounted for in the system design kWh/day shown in Table 6.

scale procurements could reduce this unit price. Prices of inverters and other components are based on current prices from the wholesale solar supplier African Energy. However, it should be noted that these prices do not include shipping or other logistics costs.[17] In addition, Madagascar has less average sunlight per day along the east coast than other countries in Sub-Saharan Africa; insolation ranges from 3.6 to 5.2 hours of 1 kW/m² per day. In the final design, actual systems should be sized to location requirements. Figure 10 provides a map of the global horizontal irradiance (GHI) for kWh/m² per day using long-term average data from 1999–2018.[18]

Figure 10. GHI in kWh/m²-day overlayed with the health facilities (2023)



17 The Malagasy tax code exempts solar panels, wind turbines and batteries from both VAT and import duties – see https://www.get-invest.eu/market-information/madagascar/#:~:text=The%20Malagasy%20tax%20code%20provides,both%20VAT%20and%20import%20duties.

18 See - https://solargis.com/maps-and-gis-data/download/madagascar

System sizing employs inverters rated at about the Wp of the solar panels to get them with MMPT chargers adequate for the system size. Batteries are priced for lithium banks at current prices of USD 399/kWh storage for 48V storage with 1.5 days of autonomy and 80 percent depth of discharge. The autonomy may seem a little short, but there is also 30 percent added capacity for future use (the additional kWh/day listed in the table below, versus the consumption in the table above), plus 20 percent oversizing of solar panels for 25-year degradation, increasing actual charge capacity during the day. This will allow reassessment of the system or paralleling of a second system as new equipment adds loads if needed in a particular location. The results of the electrification plan were used to determine if a particular facility required an off-grid system or a hybrid system to satisfy its electricity and CCE energy requirements. Note that the solar standalone kit designed for the CSBs is the same for both off-grid and hybrid-use cases as there is little change in cost or sizing requirements and a strong incentive to standardize this design to enable economies of scale during the procurement/installation of these systems. The results of this analysis are presented in the next section of this report.

Table 6. Health facility solar dimensioning and budget

Units	Size 1 CSB/DIS/MAT	Size 2 CHD/SDSP	Size 3 CHR/DRSP/CRNM	Size 4 CHU/DPEV
System Size in kWh/day	1.373	29.41	133.29	146,060
Array Capacity (kWp)	0.479	8.4	38.0	41.7
Off-grid Cost USD	$1,225	$27,076	$117,457	$127,964
Hybrid Cost USD	$1,225	$15,544	$65,206	$70,710

Medical Cold Chain Analysis

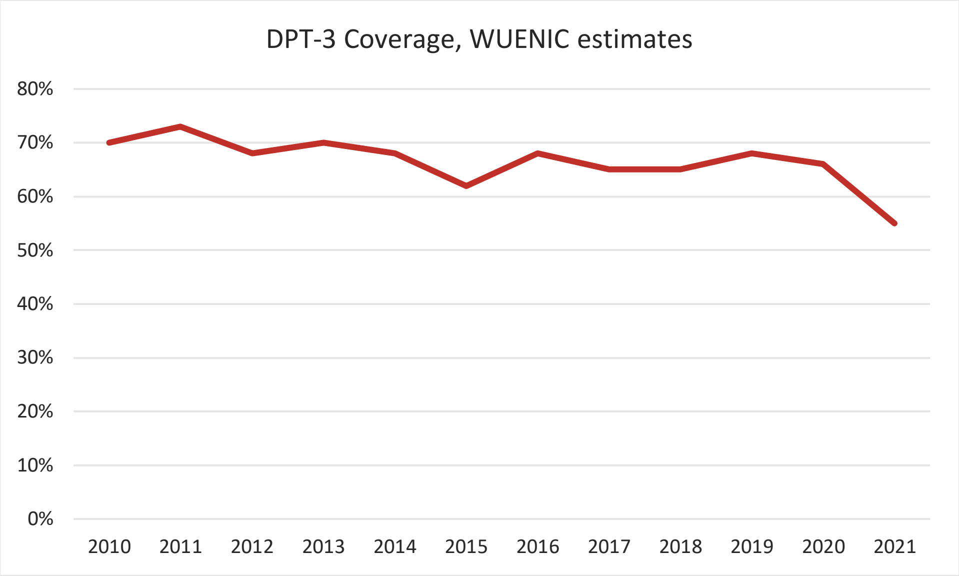
Routine vaccine and COVID-19 vaccine summary

Madagascar offers routine immunization for children. The country is no exception to the global decline in routine vaccine coverage during the COVID-19 pandemic, due to lost access to healthcare facilities, greater hesitancy related to vaccines and competing priorities of healthcare workers. The estimated DPT-3 coverage rate dropped from 68 percent in 2019 to 55 percent in 2021, which is demonstrably low for the southern African region and has exacerbated an existing equity gap in vaccine access.[19] DPT-3 coverage is a standard used to indicate performance of the immunization programme as it traditionally shows that a child has received all vaccines in the immunization schedule. There has been some improvement in DPT-3 coverage in recent months according to the administrative data, increasing to 71 percent in February 2023, yet still falling short of reaching the target of 90 percent. When looking at DPT-3 coverage by region (Figure 11),

[19] Performance de la Vaccination de Routine, Janvier 2023. Direction du Programme Elargi de Vaccination.

the notable discrepancies across the regions indicate inequitable coverage and pockets of higher risk of vaccine-preventable diseases. It is important to note that one region reports higher than 100 percent coverage; coverage is calculated based on population estimates and administrative data reported from immunization sessions, both of which can be inaccurate, resulting in the illogical coverage rate higher than 100 percent.

Figure 11. DPT-3 coverage rates 2010–2021 (Source: WHO/UNICEF WUENIC estimates)



Additionally, the vaccination coverage is shown in Figure 12a and the COVID-19 vaccination campaign in Madagascar is included in Figure 12b, which shows somewhat similar trends as the DPT-3 vaccination coverage, but also has relatively low coverage in highly populated areas. Since the COVID-19 vaccination rates are below 30 percent in all regions of Madagascar, it seems to suggest that accessibility issues may not be the primary constraint and perhaps vaccine hesitancy is a contributing factor. As COVID-19 vaccination rates approach 100 percent, it is possible that accessibility and cold chain limitations could play a more decisive role in determining vaccination disparities among regions.

Figure 12. a) DPT-3 coverage by region (February 2023; Source: MoH administrative data); b) COVID-19 coverage by region (April 2023; Source: MoH administrative data)

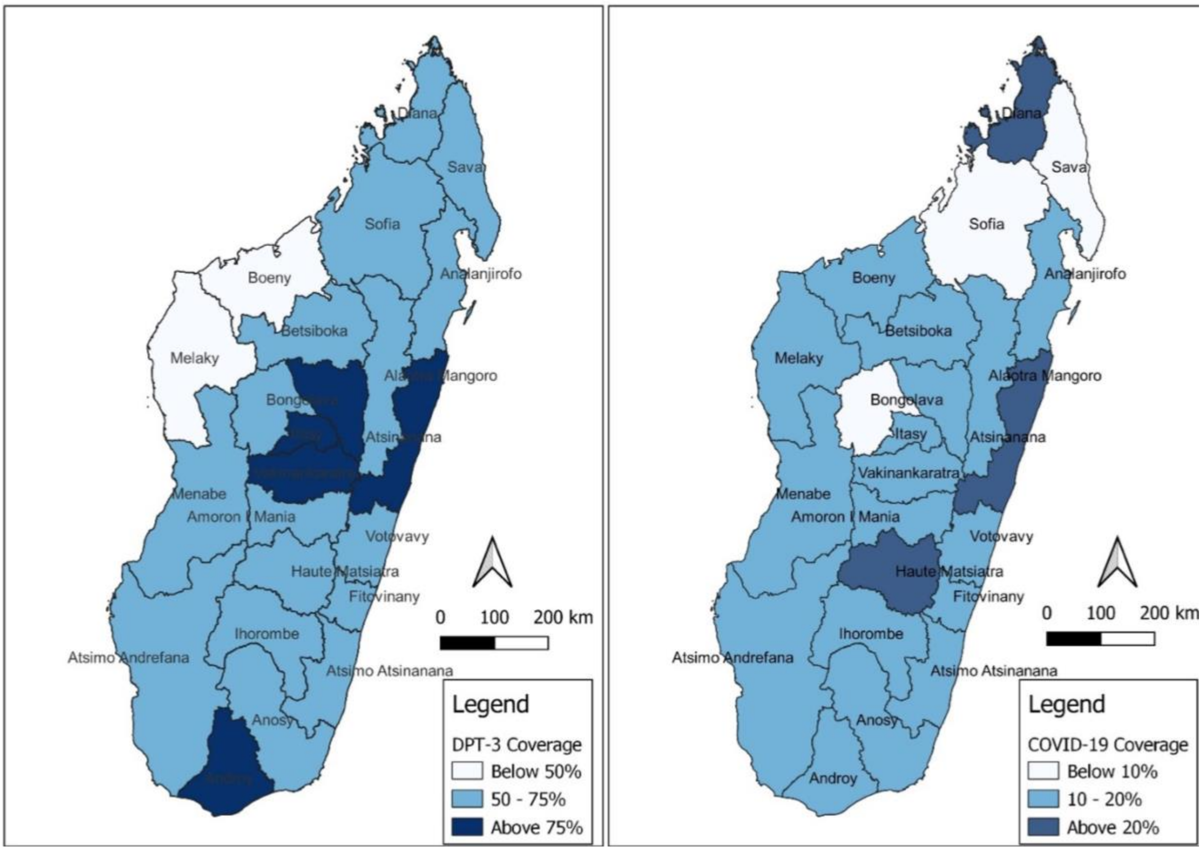
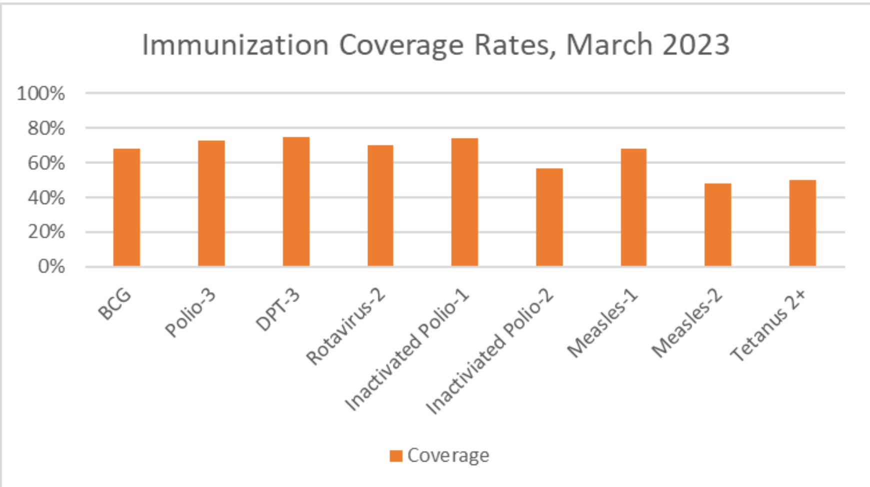


Figure 13. Current immunization coverage rates, March 2023
(Source: MoH administrative data).



Vaccines are offered at most healthcare facilities and through community outreach services. Outreach efforts are prioritized for remote areas with low vaccine coverage. Outreach efforts include demand generation and sensitization activities to encourage caretakers to get their children vaccinated. Healthcare workers travel to these remote areas, transporting vaccines in small cold boxes, to provide this service.

The country is focused on reaching “zero-dose” children, operationally defined by GAVI and others as children who have not received the first dose of the DPT vaccine. Globally, it is estimated that more than 17 million children went unvaccinated in 2020; while the estimate is unknown specifically for Madagascar, it is a safe to assume that the decline in coverage indicates that there is a significant number of children who have not been vaccinated. [20]

The Covishield COVID-19 vaccine was introduced in Madagascar in May 2021. The number of people who are completely vaccinated is about 2.6 million (about 18 percent of the target population), falling short of the target of reaching 50.5 percent of the population.[21] The country has been using mass campaigns to encourage uptake of the vaccine, particularly in remote areas, combined with sensitization and promotion efforts. As the interest and urgency of COVID-19 has waned, so has the uptake of the vaccines. As of August 2023, the vaccine was offered in healthcare facilities through routine services although not widely available.

Analysis of vaccine storage and distribution: Cold Chain Equipment Assessment

Madagascar’s health system is organized into four levels: basic, district, regional and central. These different levels are linked to each other through an established referral system.

The national cold chain inventory that was completed in November 2022 identifies 2,894 pieces of cold chain equipment (CCE) in good working order, with an additional 364 pieces said to be working but in need of repair installed across the multiple levels of the system. The equipment in good working order includes 14 walk-in cold rooms, six ultra-cold chain (UCC) freezers for the Pfizer COVID-19 vaccine, 2,597 performance, quality and safety- (PQS) certified refrigerators, 211 PQS-certified freezers and 66 non-PQS-certified devices (Figure 14). Most of the equipment that is being used and is acceptable by global standards (i.e., PQS approved and within a reasonable age of 15 years or less) is functioning well (Figure 15), with a small percentage that needs to be repaired and a small percentage that is no longer working. It is unknown if the CCE that is not working has been decommissioned and thus removed from the health system and has simply not been updated in the inventory, or it remains in healthcare facilities and on the inventory. It is important to note that the World Health Organization (WHO) recommends only PQS-certified devices as they have been designed and tested for vaccines specifically and provide more reliable and consistent performance. The analysis focuses mainly on PQS equipment.

[20] Massive vaccination campaign in Madagascar to eradicate polio. GAVI, the Vaccine Alliance. August 8, 2023. https://www.GAVI.org/fr/vaccineswork/campagne-vaccination-massive-madagascar-eradiquer-polio
[21] Ministry of Health, Madagascar, administrative reporting, August 2023.

Figure 14. Résumé Summary of PQS and non-PQS equipment

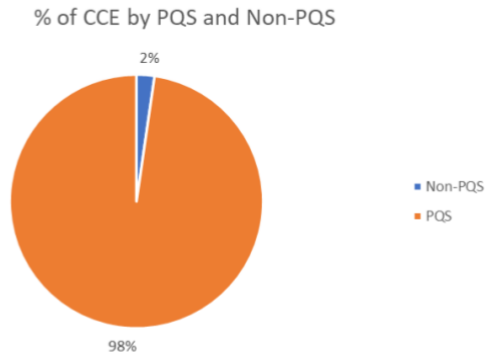
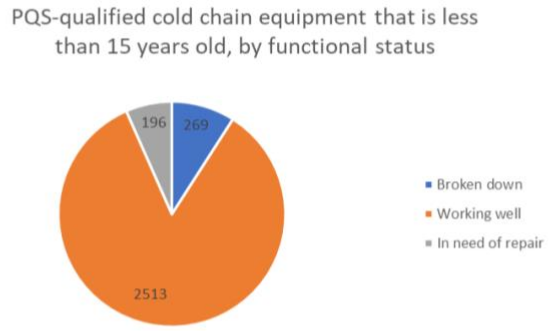
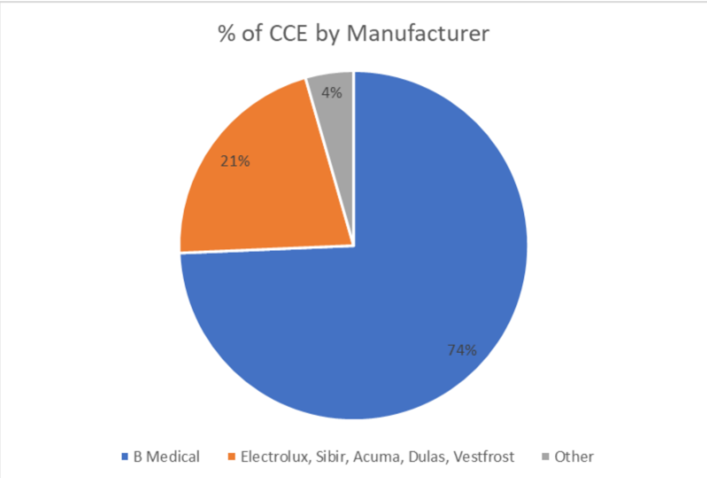


Figure 15. Functional status of PQS equipment less than 15 years old



The national cold chain inventory identifies approximately 39 different manufacturers for this CCE, with the vast majority (2,151 out of 2,898 pieces of equipment, all PQS certified) manufactured by B-Medical Systems-/Dometic. Other manufacturers, including Acuma, Electrolux, Sibir, Dulas and Vestfrost make up a second tier, each having between 75 and 175 pieces of equipment (all PQS-certified). This has implications on the maintenance system as multiple manufacturers and models require different spare parts and expertise to maintain and repair.

Figure 16. Percentage of CCE by manufacturer



Tables 7 and 8 summarize the working pieces of CCE in public sector healthcare facilities, by installation year. The oldest piece of CCE that is reported to still be in working order, according to the national cold chain inventory, is a non-PQS-certified appliance installed in 1980. It is surprising to note that 15 pieces of non-PQS equipment were procured and installed in the past three years, as typically countries have moved away from non-PQS equipment as per WHO guidance and UNICEF procurement preferences to not procure non-PQS equipment through projects funded by GAVI; these purchase decisions are somewhat of an anomaly compared to global trends. Another significant observation is that 34 percent of all equipment available to the Ministry of Health (MoH) in its inventory is not functional, implying that there may not be a clear decommissioning process to remove old equipment from the system.

Table 7. Summary of cold chain equipment age and PQS status
(Source: MoH 2023)

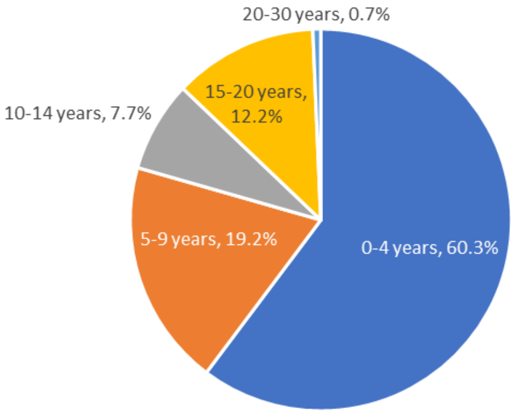
Year of installation	Non-PQS	PQS	Total	% of total
1980-1999	1	14	15	1%
2000-2009	14	385	399	14%
2010-2014	6	210	216	7%
2015-2019	30	1049	1079	37%
2020-2022	15	1168	1183	41%
Unknown	0	2	2	0%
TOTAL	**66**	**2828**	**2894**	**100%**

Table 8. Summary of functional status of PQS-approved cold chain equipment
(Source: MoH, 2023)

Manufacturer	Functional	In need of repair	Non-functional
B Medical Systems (Domestic)	2,151	174	145
Electrolux	164	71	436
AUCMA	131	3	8
Sibir	155	80	667
Dulas	84	1	3
Vestfrost	79	5	27
Haier	27	0	2
Zero Appliances	15	15	309
EURONON	9	1	1
Huurre	4	1	0
Sun Frost	2	0	1
PHILLIPS	1	0	0
Dometic	0	0	2
Zhendre	0	0	1
TOTAL	**2,822**	**351**	**1,602**

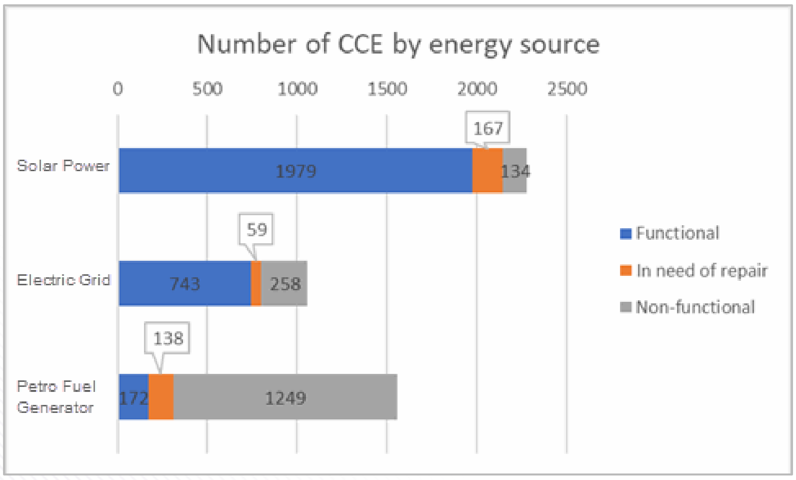
The average lifespan of an element of CCE is estimated to be about 10 years if properly maintained. About 60 percent of the PQS equipment is less than four years old (Figure 17), which implies a younger cold chain system that has the potential to be functional for another five to seven years with basic maintenance. About 12 percent of CCE is 15–20 years old and less than one percent is more than 20 years old; while impressive that these pieces of equipment are still working, the MoH should plan for replacement as funding becomes available.

Figure 17. Age of functional PQS equipment



The majority of available CCE is solar direct drive (SDD) (Figure 18), reflecting both the limited extent and lack of reliability of the electricity grid. SDD technology offers a reliable solution to underpin the cold chain for vaccines. SDD equipment is linked to solar panels that are designed only for the equipment and are not available for other uses, such as lamps or cell phone charging. SDD's high rate of functionality also reflects the relatively recent installation of these pieces of equipment. Interestingly, the country still has some CCE that relies on petrol or propane gas, which has not been recommended for use in more than a decade. Many of this gas-powered CCE is no longer functional. As the electrical grid expands and mini-grids are developed in rural regions, facilities with solar CCE can continue using the equipment until standard AC equipment, typically less expensive than SDD equipment, can be procured. Once AC power access is more prevalent in rural areas, the SDD equipment can be reallocated to facilities designated for standalone solar electrification or to replace older, non-functional equipment.

Figure 18. Number of CCE by main energy source (Source MoH, 2023)



*Note: Solar power CCE is equipment that runs on its own solar panels; the system is not available for other uses, such as for lamps or cell phone charging.

Analysis of vaccine storage and distribution: Capacity Utilization Assessment

Capacity utilization is calculated based on the vaccine quantity required as per the vaccine schedule, the target population of each facility, vaccine characteristics and the total net cubic liters of the PQS-certified equipment available and functioning at the facility. Key results of the analysis are here, with further details below:

- At the facility level, the CCE that is available and in use is relatively young, functions well and in most facilities (68 percent), uses less than 10 percent of the physical capacity.
- 20 percent of facilities do not have functioning CCE and thus are not providing vaccines on a regular basis.
- Most districts have sufficient space, but nine districts need additional capacity.

Information is available on the cold chain capacity of 2,506 of the 2,832 facilities (88 percent) identified at the basic health centre (CSB) level. Of the facilities for which cold chain capacity information is available, the majority (68 percent) of healthcare facilities (CSB1 and CSB2) are using less than 10 percent of their cold chain space, and are categorized as underutilized (Figure 19). This indicates room for new vaccines, growth in population and flexibility with the distribution schedule, for example during the rainy season when roads are inaccessible to most healthcare facilities.

However, 557 of the 2,506 facilities (22 percent) at the CSB level, for which capacity information is available, are listed as having no capacity either because they do not have a refrigerator or because the refrigerator that they have is not currently functional. These 557 facilities without capacity are spread out over all 23 regions of Madagascar, and 92 of the 114 districts, though there is some concentration in the northeast regions including Atsinanana (67 facilities), Alaotra Mangoro (58 facilities) and Analanjirofo (45 facilities). This indicates a gap in services and a need for new equipment most immediately targetting those facilities that do not have functioning equipment and with a longer-term plan to replace older equipment, using 10 years as an estimate of lifespan.

Information is available on the cold chain capacity of all 114 district-level storage sites, an important storage point in the vaccine supply chain. The majority (86 percent) of these districts fall into the “appropriate utilization” category of their cold chain/refrigerator space, indicating there is sufficient space for the current vaccine schedule and distribution frequency. The nine districts that are either constrained (Ambohidratimo, Fenoarivo Atsinanana, Ampanihy, Toliary II and Befanadriana), are over capacity (Toamasina I and Sambava) or have no capacity (Befotaka and Andapa) are most likely currently sharing space with local hospitals, adding a strain to other CCE, and adding an extra burden on the supply chain managers to manage multiple systems. Table 9 below summarizes these facilities and how much additional cold chain space would be needed to bring them below 80 percent utilization. Freezer space is sufficient in most districts; freezers are used only for the oral polio vaccine down to the district level. Storing the vaccine in a freezer is not a requirement but optional at the district level. This vaccine is stored in regular CCE (refrigerators) at the facility level.

Table 9. District stores that are currently constrained or over capacity

Region	District	Current capacity utilization	Additional liters of capacity needed to fall below 80% capacity utilization
Analamanga	Ambohidratrimo	96%	79
Analanjirofo	Fenoarivo Atsinanana	99%	57
Atsimo Andrefana	Ampanihy	93%	60
Atsimo Andrefana	Toliary II	81%	5
Atsimo Atsinanana	Befotaka	No cold chain capacity	57
Atsinanana	Toamasina I	116%	109
Sava	Andapa	No cold chain capacity	32
Sava	Sambava	141%	184
Sofia	Befandriana	88%	23

Figure 19. CCE capacity utilization by percentage of districts and healthcare facilities in the different categories, current status and in 10 years assuming population growth

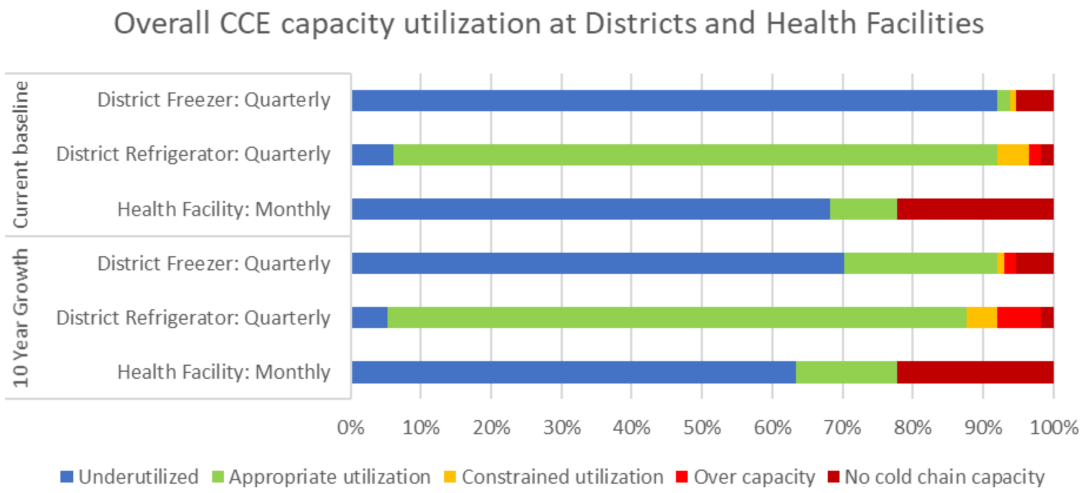


Figure 20. *CCE capacity utilization at +5^{0}C for district health facilities (SDSPs) (%)*

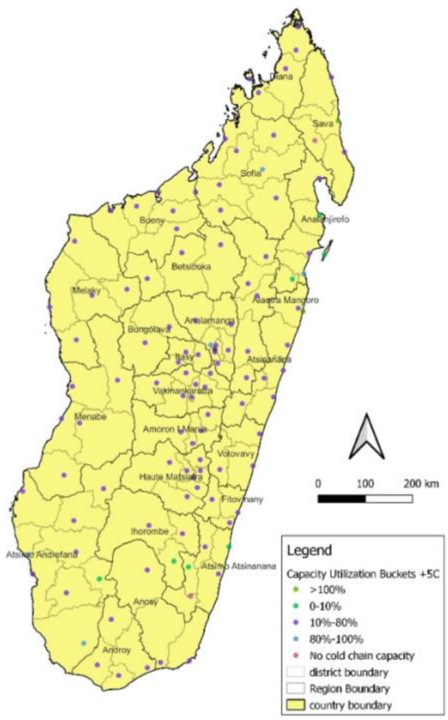
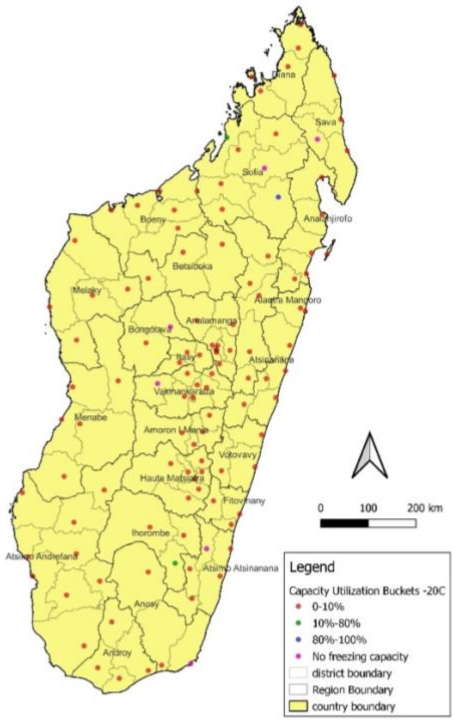


Figure 21. CCE capacity utilization at -20^{0}C for district health facilities (SDSPs) (%)



The analysis also considered population growth in the next 10 years, assuming a 2.4 percent growth per year as per current estimates and the impact on the CCE capacity utilization (Figure 19). Results show that there will be minimum change at the healthcare-facility level since so much CCE is currently underutilized and has sufficient space for growth. Five district stores out of 114 will shift into the "over capacity" range without any new equipment installed. In terms of new vaccine introduction in the country and thus the impact on the CCE, no new vaccines are planned for introduction in the immediate future. As the malaria vaccine will initially be available only in limited supply, GAVI did not select Madagascar to be one of the initial countries for introduction (as of 2023). As the supply stabilizes and the malaria vaccine is potentially introduced in Madagascar, the capacity at the healthcare-facility level should be sufficient, with some constraints at district level. However, this will be several years in the future as the electric grid is expanded and more CCE is procured and installed.

In addition to the equipment described above, the immunization programme's CCE list contains 107 pieces of CCE identified as located in specific facilities that were included in the master facility list but whose functional status is marked as "new, not installed." This includes 86 units of SDD equipment, 20 conventional electrical units and, surprisingly, one gas-powered unit. In terms of the funders supplying this equipment, the new equipment includes 36 units funded by UNICEF, 29 units funded by the World Bank, 17 units funded by GAVI, three funded by the state and five funded by other funders or with funding information unknown. The delay in installation of the CCE that was procured by the World Bank is linked to a delay in funding that has since been resolved; the installation process for the majority of the CCE should have been completed by the end of 2023. The programme has a small team of 13 cold chain technicians (three at the national level and 10 at the regional level), which makes it difficult to respond to all maintenance and installation needs for the country. If this equipment is assumed to now be installed, this changes the utilization picture described above only slightly, reducing the number of CSBs that do not have any CCE capacity from 557 to 500, and reducing the number of districts that have constrained capacity (between 80 percent and 100 percent) from five districts to three (both Toliary II and Ampanihy would receive electric refrigerators). Of these 107 pieces of new equipment, nine are solar or electric grid units that are slated to go to facilities that currently have working petrol units, thus updating the equipment with a more efficient system; the one new petrol unit is going to a facility that currently has a working petrol unit, and 58 are slated to go to facilities that have no working CCE.

Cold chain equipment needed to meet current and future needs

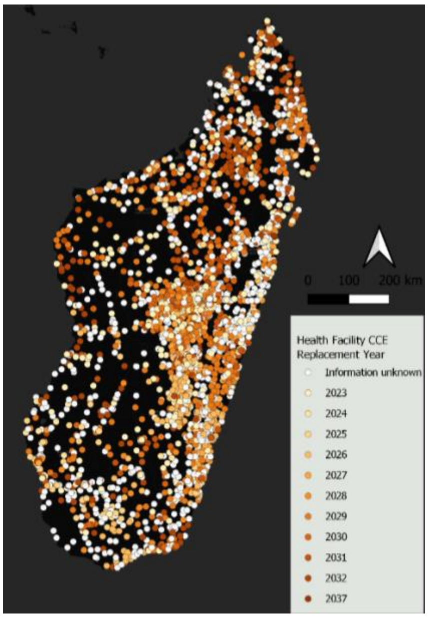
To plan for cold chain needs, the analysis looked at current needs and longer-term needs through 2030 considering the expected lifespan of CCE. Table 10 below describes the new equipment that would be needed to meet *current needs,* while Figure 22 provides a map of when CCE replacement would need to take place per health facility. This takes into account the equipment that is new but not yet installed described above; and then provides new equipment to facilities that need cold chain as they are providing immunization services but currently have no working CCE; and provides additional equipment to facilities that are currently constrained or over capacity. In all cases, the facilities receiving the new equipment are described in the management file of the Directorate of the Expanded Immunization Programme (DPEV) as not having reliable access to electricity, so in all cases the suggested equipment to be procured is solar. Equipment has been bucketed by the typical size of PQS-approved equipment, with the smallest (and therefore least expensive) unit possible used that meets the need of a facility. For example, if a facility needs five liters of refrigeration capacity and currently has none, they will receive a 30-liter refrigerator. If a facility needs 31 liters of additional capacity, then a 30-liter refrigerator will not meet their needs, so the next size up is assigned (60 liters).

Table 10. Additional cold chain equipment needed to meet current needs

Capacity of CCE to be procured (liters)	Number of refrigerators needed	Number of freezers needed
30-liter CCE	500	7
60-liter CCE	3	0
90-liter CCE	1	0
120-liter CCE	1	0
120+-liter CCE	1	0

* *Not included in the above table is a need for 18,187 liters of space for DPEV.*

Figure 22. CCE replacement year



As cold chain needs and population both grow between now and 2030, equipment needs will also grow. However, if the equipment needed to meet current needs described in the previous table is procured, then additional equipment needs in 2030 would be modest. That is, if a facility currently has a need for five liters of capacity, and Madagascar provides it with a refrigerator with a 30-liter capacity, then although the facility's capacity needs will grow over the next six years, they will not exceed the capacity provided by the newly installed equipment. By 2030, therefore, if the equipment described in the previous table is procured, additional equipment needed to meet the needs of facilities that would grow beyond 80 percent utilization (that is, they would be constrained) includes only four refrigerators with a 30-liter capacity; one with a 60-liter capacity; three with a 90-liter capacity, two with a 120-liter capacity and one with over a 120-liter capacity (this facility would need 199 additional liters of capacity to go below 80 percent utilization). No additional freezers would be needed.

For the most immediate current needs, the immunization programme has recently applied to GAVI to procure 365 new pieces of CCE, all SDD equipment, targetting the CSB1 and CSB2 levels. Of these new pieces of equipment, 300 are slated to replace non-functioning CCE; the remaining 65 will be installed in facilities that did not have CCE previously, thus extending the reach of the immunization programme. This will contribute to reducing the percentage of healthcare facilities without functioning CCE and with optimal and efficient equipment, yet more equipment will still be required to ensure vaccine storage is available at all facilities. The application is expected to be approved with an assumption that the new equipment would arrive and be installed in 2024. These pieces of equipment should come with a requirement from the manufacturer to also install the CCE and to respond to maintenance issues while under warranty (five to seven years typically). Through this procurement, the country is moving away from older equipment to newer SDD systems.

For *longer-term planning* to replace old and unreliable equipment, a second analysis is provided. The expected lifespan of a vaccine refrigerator or freezer is 10 years; walk-in cold rooms are expected to last 20 years (according to WHO standards). Although most of the currently functional equipment in Madagascar was installed relatively recently, Madagascar should make plans to replace some of its (very) old equipment that is currently in service and make plans for those pieces of equipment that will reach the end of their expected lifespan by 2030. Table 11 lists the number of pieces of equipment that will need to be procured between now and 2030 to replace currently functioning equipment that either a) is not PQS-qualified; b) has already reached the end of its expected lifespan or will do so by 2030; or c) is marked in DPEV's cold chain inventory as not currently functional and in need of repair or replacement.

Table 11 lists the kind of equipment that will need to be procured based on the existing equipment, using the following logic:

- If the unit being replaced is solar-powered (SDD), the replacement unit will also be solar powered
- If the unit being replaced is electric (direct-current) or gas powered, the replacement unit will be:
    - Electric if the facility is listed in DPEV's facility management file as having reliable access to electricity for at least 16 hours per day[22]
    - Solar otherwise
- Freezers, refrigerators and walk-in cold rooms (positive temperature storage and freezing storage) will be replaced with equipment of the same type (i.e., with the same functional characteristics in terms of temperature range, etc.)

Table 11 provides an estimate of equipment needed in the coming years. It is important to note, however, that the numbers and types of equipment in the table are illustrative only and would need to be validated based on the reality of the equipment performance, true capacity needs and new cold chain technology that may become available in the coming years.

Firstly, as the electrical grid expands and becomes more reliable, less solar equipment will be necessary. Additionally, investing in a strong maintenance system now would contribute to extending the lifespan of a piece of equipment. Finally, technological evolutions may also permit different procurement choices for facilities with intermittent or no access to mains electricity. Broadly speaking, conventional compression refrigerators have several advantages over SDD units. One is that thermostatic control precision is generally higher. Another is that the overall energy efficiency is greater, mainly because the cooling system operates at a lower temperature differential to ambient than is required to freeze phase change material (PCM). A third is that initial investment is lower where AC power is already available. The SDD refrigerator's principal advantage is that it avoids the cost of storage batteries required by off-grid solar electric systems to keep a small refrigerator running. However, recent battery developments have caused many of these system prices to drop to the point that storage battery and inverter cost is competitive with the price differential for purchasing many of the PQS SDD refrigerator units currently on the

[22] Note that although the GAVI guide to cold chain procurement recommends conventional (non-solar) equipment for facilities that have access to electricity for at least eight hours per day, it also recommends solar equipment if a facility experiences power cuts of 48 hours or more. Because the length of power cuts are unknown, and because unreliable power reduces the life expectancy of cold chain equipment and can pose a threat to vaccine quality, we are using 16 hours as the cutoff here.

market. This is a dynamic difference that must be monitored, but with solar energy receiving greater development efforts worldwide, it is reasonable to expect that its cost efficiencies will improve faster than SDD refrigeration technology will.

Table 11. Number of units of new equipment needed to replace existing equipment, by year and by type

Year needed	Walk-in cold room (positive storage)	Electric Freezer	Electric Refrigerator	Solar Freezer	Solar Refrigerator
Dès que possible	2	99	191	18	1003
2024		1	2		23
2025	1	2	2		93
2026			1		254
2027		2	2		68
2028	2		13		107
2029		20	13	1	556
2030	1	6	10		209

A note regarding walk-in cold room needs described in the table above: the two walk-in cold rooms that are listed as in need of replacement ASAP are units that were installed in 2013 and 2014 and so would normally be expected to last through 2030, but are listed on DPEV's cold chain management tool as not working and in need of repair. The two units that are listed as needing replacement in 2028 are at DPEV's central warehouse, although as of mid-2023 DPEV was finalizing a new warehouse in Antananarivo; the new warehouse would likely make replacing these old cold rooms unnecessary. All other walk-in cold rooms listed above are in regional-level facilities, which are not currently used to store vaccines, apart from one in Melaky (needed ASAP above) that is an exceptional region that distributes from the regional level. Three of the above walk-in cold rooms (needed ASAP and in 2025 and 2030) are not needed for the vaccine programme but may be needed for other cold-chain products outside the scope of this analysis.

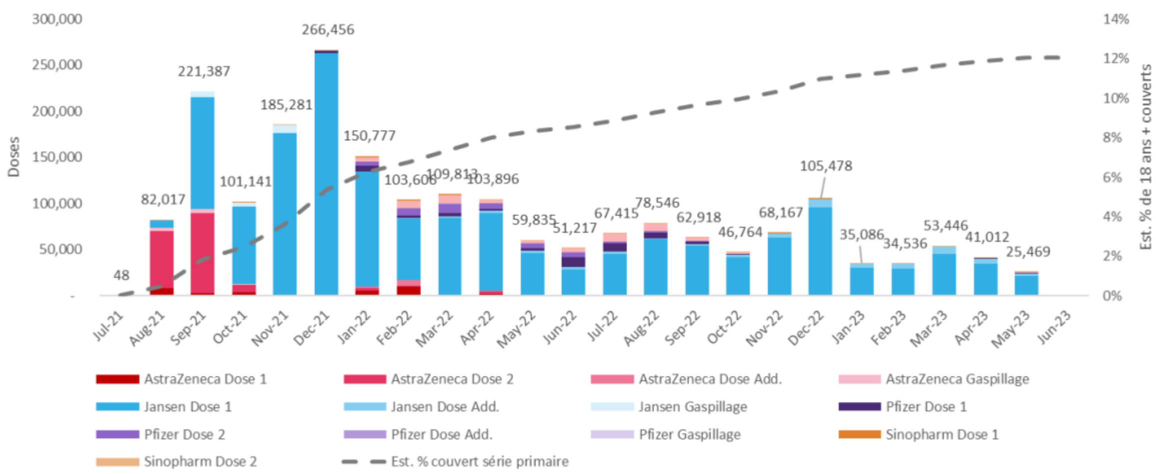
According to World Health Organization's PQS catalogue, costs of CCE that are typically used in healthcare facilities and district-level stores range in price from USD 2,500 to USD 6,000, depending on the make, model, size and whether they are solar or grid dependent. UNICEF is often the main procurement agency for CCE for LMICs, which factors into their ability to negotiate prices, warranties and service bundle providers for installation and maintenance. As such, it proves difficult to determine an exact price required for new equipment in the next decade; however, this analysis provides an estimate of the amount of equipment needed that can be revised in the coming years. It is important to note that these cost estimates are provided as capital expenditure projections and not a procurement plan.

Monitoring the temperature of the CCE is important to ensure its functioning and, ultimately, the quality of the vaccine. Understanding the performance of the CCE allows for more proactive planning for replacement and repair. To support active temperature monitoring, the current GAVI application also requests FridgeTags, which actively monitor and report temperatures from the CCE. Healthcare workers typically track CCE temperatures twice daily using the FridgeTag to record the temperature and any alarms on temperature monitoring forms. FridgeTags do not transmit data to a dashboard. FridgeTags are in common use in Madagascar at the facility level. Higher level walk-in cold rooms typically have more advanced remote temperature monitoring devices that send SMS alerts when there is a change in temperature that requires immediate action and send data to a dashboard for real-time monitoring.

Figure 23. FridgeTag used in CCE to monitor temperatures

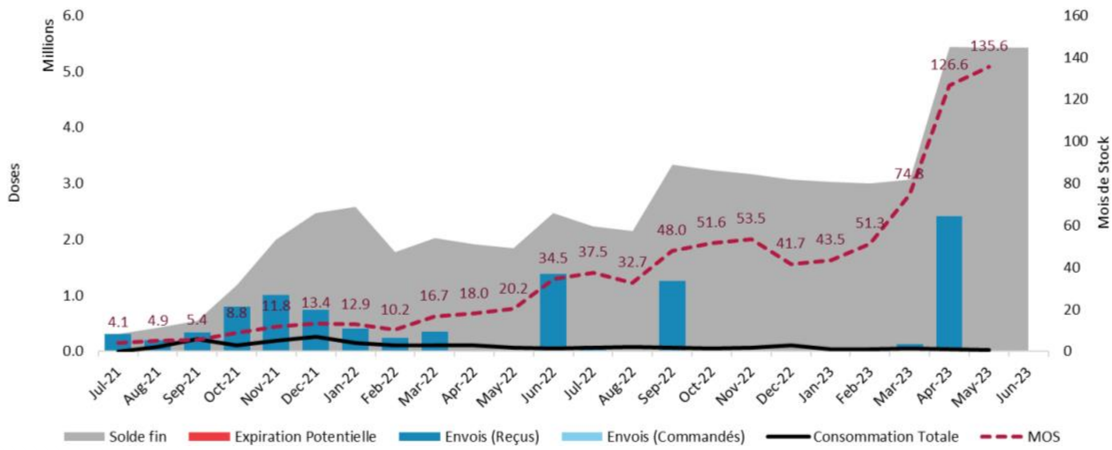
Madagascar introduced the COVID-19 vaccine in May 2021, mostly using large campaign efforts to reach the target population. The country installed six pieces of ultra-cold chain (UCC) equipment at the national and district levels specifically designed for the Pfizer vaccine, which requires much colder temperatures than other vaccines. Figure 24 shows consumption of the COVID-19 vaccine over time, in terms of both doses administered and wasted (through having to discard any remaining doses in a vial at the end of a vaccination session); after initial large-scale campaign efforts and interest in the vaccine, vaccine uptake has declined over time. It is currently offered through routine services at healthcare facilities as available, although not prioritized. Stock decisions are based more on vaccine availability rather than target population, which has minimum implications for the cold chain capacity utilization. Analysis shows that healthcare facilities have sufficient CCE space to accommodate this approach for the COVID-19 vaccine.

Figure 24. Consumption and administration of COVID-19 vaccines over time



The Expanded Programme on Immunization (EPI) team managed the large shipments of the COVID-19 vaccine over the past two years, adjusting stock as necessary to accommodate cold chain space. The priority for this vaccine is slowing down as the pandemic has shifted to an endemic phase, yet the country still has large stock levels, as seen by the months of stock (MoS) in Figure 25. Sinopharm makes up most of these vaccines in stock and their expiration in August 2022 has freed up a significant portion of the national-level cold chain and some of the space in the district stores. The MoH will continue to prioritize the Pfizer vaccine for those who received the first dose to complete the second dose.

Figure 25. COVID-19 vaccine stock management over time



Vaccine distribution

The MoH in Madagascar has five trucks, two of which are refrigerated, to ensure vaccine distribution from central level to district level, yet only one cold truck is currently functioning (see Figure 26 for an example of this vehicle). The central level delivers vaccines to districts with good road access on a quarterly basis. UNICEF provides two additional trucks to fill in the current gap and to access the harder-to-reach areas (see Figure 27). Facilities collect vaccines monthly by a variety of transportation methods including government motorcycles when available, public transportation (tuk tuk or taxi), sometimes by boat in certain geographical areas, zebu carriage, and sometimes on foot.

Figure 26. An example of a refrigerated cold truck

Figure 27. Vaccines being loaded on a truck in Madagascar for delivery

Health workers use cold boxes and vaccine carriers for distribution when a cold truck is not available. While this is the standard approach, temperatures within cold boxes and vaccine carriers can be variable and difficult to monitor.

As the current vaccine distribution system operates, UNICEF provides significant support at the national level. Additional cold trucks could be helpful to reduce the dependency on UNICEF for distribution from national to the district level; however, as seen by four of the five MoH-owned vehicles currently not working, any new trucks need to have a strong maintenance system to ensure long-term functionality. Additionally, other distribution approaches such as outsourcing to a private company could be explored to create a system that is more reliable, performance-based focused and allows the MoH to focus on healthcare instead of transport management. As for last-mile delivery, the burden currently falls on facility-level staff to transport vaccines from the district level, which is typically understood by supply-chain designers to be inefficient and often unreliable. In a system design analysis concluded in March 2020 by JSI for the MoH and the immunization programme, one of the scenarios included using direct delivery for last mile, to place the responsibility on the district level for delivering to the facilities. Decision-makers at the time decided that more information was needed to further explore this possibility to ensure last-mile delivery. With this analysis for the Integrated Energy Plan (IEP), it may be an opportune time to revisit the system design analysis to explore the level of interest to invest in a more reliable last-mile delivery system.

Figure 28. Piece of cold chain equipment typically used in a health facility

(Source: JSI, 2022)

Figure 29. Vaccine carriers used for smaller distribution or outreach to communities

(Source: World Health Organization 2022)

Medical Cold Chain Energy Requirements and Cost Analysis

Based on data from the MoH, in 2023, there were 3,053 active healthcare facilities in Madagascar. In the Madagascar IEP companion report on universal electrification by 2030, all structures and buildings in Madagascar are modelled in terms of their least-cost electrification modality. Figure 30 provides the reported electricity access by facility (based on data provided by the MoH), while Figure 31 categorizes the healthcare facilities as to whether they are geospatially located within an area with an existing distribution system based on the Madagascar IEP electrification analysis. The results of the electrification analysis are provided in Figure 32, which illustrates the facilities that are currently served by the JIRAMA national grid as well as those that will be electrified by 2030. Some of these newly electrified facilities will result from grid densification and expansion, both in the existing JIRAMA interconnected grids (surrounding Antananarivo) and the nearly 100 isolated JIRAMA networks throughout the country. Those facilities served by densification and expansion would be likely candidates for hybrid solar and battery storage solutions to serve as backup power for periods of intermittency in grid power, whereas other healthcare facilities to be powered by future off-grid solutions are more likely to require completely off-grid standalone power systems.

Figure 30. Healthcare facilities by reported electricity access (MoH 2023)

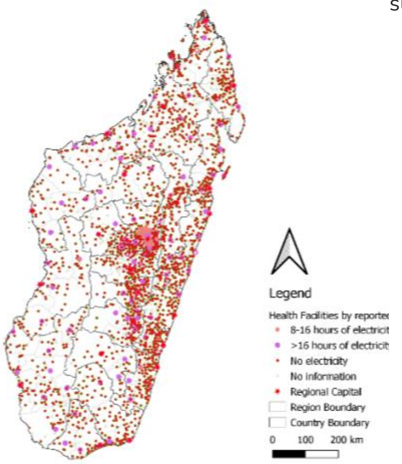


Figure 31. Healthcare facilities by whether they are geospatially located within an area with existing electricity supply or not (IEP 2023)

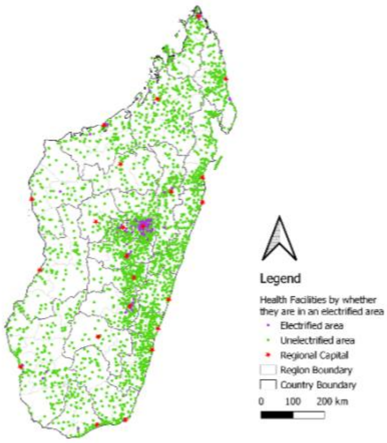


Figure 32. Healthcare facilities classified by 2030 electrification modality (IEP 2023)

Table 12 provides a summary of the count of health facilities by type and Least-cost Electricity Access Development (LEAD) support status, showing the reported hours of electricity availability (from data provided by the MoH) as well as whether the facility is geographically located within an area with known distributed electricity service (based on geospatial analysis).

Table 12. Healthcare facilities by LEAD support and by type, summarizing reported electricity access and geospatial location relative to electrified areas with distribution systems (2023)

Healthcare Facilities by Type	In Electrified areas				In Unelectrified areas				
Reported electricity access	>16 hours	8-16 hours	No Electricity	No Data	>16 hours	8-16 hours	No Electricity	No Data	LEAD electrified as of 2023
Non-LEAD facilities									
CHD					1				
RSC	1	1					1		
CHRD	3	1	11		6	9	29		
CHRR	2		2				5		
CHU	2	1	2						
CRNM			1		1		1		
CSB1		5	42	8		5	708	94	
CSB2		60	88	34		23	1121	144	
DISP/MAT		1							
DPEV	1								
DRSP	15				8				
Hospice		2							
SDSP	42		1		69		2		
LEAD Phase 1									
CSB1									17
CSB2									30
LEAD Phase 2									
CSB1			1			1	157	22	
CSB2						2	249	21	
Total	**66**	**71**	**148**	**42**	**85**	**40**	**2273**	**281**	**47**

Sustainable Energy for All (SEforALL) SDG7 Baseline Scenario

The results of the electrification analysis of healthcare facilities illustrated in Figure 31 are presented in Table 11. Each of the facilities is categorized as either grid-connected or off-grid based on 2023 data. Based on the geospatial analysis of 3,053 healthcare facilities in Madagascar, only 327, or 11 percent, were in already electrified areas in 2023, while only 262 reported having an electricity source that could provide up to eight hours of electricity. The 2,726 remaining healthcare facilities will be electrified by 2030 utilizing grid densification, grid expansion, mini-grid systems and standalone solar technologies. It was assumed that all the healthcare facilities within the existing JIRAMA networks would have been connected to the grid in 2023, so there is no grid densification potential for the healthcare sector beyond 2023. Generally, the medical facilities are among the first buildings to be electrified when electrical infrastructure is constructed, so finding unelectrified clinics within the JIRAMA service territory is unlikely. Among the remaining modalities, grid expansion and medium voltage (MV) mini-grids are generally found in large population centres and peri-urban areas, whereas the low voltage (LV) mini-grids and standalone systems are more likely to be in remote rural settings.

The investments made in each facility type are reflective of the pressing need for diverse energy solutions to meet varying demands. Notably, hybrid solutions emerge as a crucial avenue for substantial investments, especially exemplified by the pronounced investments in referral hospitals at the district level (CHRDs). As public health organizations continue to seek sustainable and reliable energy sources, the insights from this analysis underscore the importance of tailored investments to bridge energy gaps across different facility types.

In addition, the World Bank-financed LEAD project, in phase 1, has already electrified 47 level 1 basic health centres (CSB1) that will reduce the total investment by USD 104,622 as well as by 41,172 kWh/day. These healthcare facilities are not included in the count in Table 13, nor in the sizing and costing tables presented in this section. There is a plan for LEAD phase 2 which will electrify 453 facilities, reducing the total amount to be invested by USD 1,008,378 while reducing the energy demand by 396,828 kWh/day. The count of the LEAD phase 1 and phase 2 facilities is shown in Table 13, and their locations are also available within the geospatial database of the IEP.

Table 13. Healthcare facility electrification modality analysis

(Source: Madagascar IEP Electrification Plan)

Type of Facility	Facilities in on grid areas (2023)	Planned electrification modality population clusters containing unelectrified healthcare facilities (excluding facilities already electrified by LEAD Phase I)				HCF by LEAD project involvement	
		Grid Expansion	MV Mini-grid	LV Mini-grid	Standalone SHS	LEAD Phase 1 (Electrified)	LEAD Phase 2 (Planned)
CHD	56				1		
RSC	182	1					
CHRD	1	16	5	1	22		
CHRR	-	2			3		
CHU	43						
CRNM	2	1			1		
CSB1	15	75	132	74	706	17	181
CSB2	4	152	204	102	1102	30	272
DISP/MAT	1						
DPEV	15						
DRSP	5	4			4		
Hospice	1						
SDSP	2	25	10	1	35		
Grand Total	**327**	**276**	**351**	**178**	**1874**	**47**	**453**

Achieving universal electrification of healthcare facilities by 2030 will require a concerted effort, as documented in the electrification report. Nevertheless, for the medical cold chain to be robust and reliable to prevent spoilage of vaccines and ensure high-standard medical care for the entire population, electricity service must be reliable. Energy access is necessary yet insufficient to guarantee healthcare outcomes.

For healthcare facilities that are either electrified by existing JIRAMA grids or will be reached by grid expansion projects by 2030, the electric reliability could be increased by adding a hybrid standby power generation and storage system consisting of solar panels and batteries. These system assumptions and associated budgets are presented in Table 14; please refer to the section on the Parameters for Medical Cold Chain Cost Analysis for the sizing and costing assumptions used. Additionally, the MV mini-grids proposed in the electrification plan consist of major Megawatt-scale power systems that will serve thousands of consumers. These systems should be robust enough to provide reliable power and thus they will also be subject to backup/standby systems. The total investment for hybrid standby power systems for all grid-based healthcare infrastructure by 2030 is approximately USD 7 million.

Table 14. Size and budget of hybrid healthcare facilities

Size	Type of Facilities	Hybrid System Sizing			Facilities on grid (2023)	Future electrification modality[23]		Total Cost
		Energy Consumption kWh/day	PV Array Size (kWp)	System Cost		Grid Expansion	MV Mini-grid	
1	CSB1	1.4	0.5	$1,226	56	75	132	$322,425
1	CSB2	1.4	0.5	$1,226	182	152	204	$659,561
1	DISP/MAT	1.4	0.5	$1,226	1	0	0	$1,226
2	CHD	29.4	8.4	$15,544	-	-	-	$0
2	SDSP	29.4	8.4	$15,544	43	25	10	$1,212,459
3	CHR	133.3	38.1	$65,207	2	1	0	$195,620
3	CHRD	133.3	38.1	$65,207	15	16	5	$2,347,440
3	CHRR	133.3	38.1	$65,207	4	2	0	$391,240
3	CRNM	133.3	38.1	$35,136	1	1	0	$70,272
3	DRSP	133.3	38.1	$65,207	15	4	0	$1,238,927
4	CHU	146.1	41.7	$70,710	5	0	0	$353,552
4	DPEV	146.1	41.7	$70,710	1	0	0	$70,710
4	Hosp	146.1	41.7	$70,710	2	0	0	$141,421
	Total				**327**	**276**	**351**	**$7,004,852**

For healthcare facilities that will not be incorporated into the JIRAMA grid by 2030 or whose locations will not allow for inclusion in planned MV mini-grids, it is assumed that reliable distributed electricity supply will be impossible to guarantee. Therefore, these facilities will require standalone stationary solar energy infrastructure to provide all their energy needs. In other words, the LV mini-

[23] Source: Madagascar IEP Electrification Plan (2023).

grids and standalone solar kits are not sufficiently reliable to depend upon in a healthcare setting. In Table 15 the total budget of USD 7 million is calculated for adding standalone solar energy to all LV mini-grids and using PV infrastructure to bolster the clinics designated to receive only standalone solar systems.

Table 15. Size and budget of off-grid standalone healthcare facilities

Size	Type of Facilities	Off-Grid Standalone System Sizing			Future electrification modality[24]		Total Cost
		Energy Consumption kWh/day	PV Array Size (kWp)	System Cost	LV Mini-grid	Standalone SHS	
1	CSB1	1.4	0.5	$1,226	74	706	$956,241
1	CSB2	1.4	0.5	$1,226	102	1102	$1,476,044
1	DISP/MAT	1.4	0.5	$1,226	0	0	$0
2	CHD	29.4	8.4	$27,076	0	1	$27,076
2	SDSP	29.4	8.4	$27,076	1	35	$974,738
3	CHR	133.3	38.1	$117,457	0	0	$0
3	CHRD	133.3	38.1	$117,457	1	22	$2,701,514
3	CHRR	133.3	38.1	$117,457	0	3	$352,371
3	CRNM	133.3	38.1	$117,457	0	1	$117,457
3	DRSP	133.3	38.1	$117,457	0	4	$469,829
4	CHU	146.1	41.7	$127,964	0	0	$0
4	DPEV	146.1	41.7	$127,964	0	0	$0
4	Hosp	146.1	41.7	$127,964	0	0	$0
	Total				**178**	**1874**	**$7,075,270**

In deriving the system sizes presented in Tables 14 and 15, a complete load profile and energy consumption forecast was created based on best practices, publicly available health facilities assessment reports and field visits in Madagascar. The energy consumption (kWh/day) is also included in the tables. The solar PV sizing is based on the load profiles and an indicative solar resource profile in Madagascar. The hybrid system sizing assumes the JIRAMA grid operates 12 hours daily, whereas the off-grid systems assume zero hours of external power supply. Note that the costs associated with conventional backup thermal generation are not considered in this analysis, to minimize greenhouse gas (GHG) emissions across the IEP portfolio.

In addition to the analyzed costs for healthcare electrification, Table 16 provides an estimate of the capital cost of the equipment needs presented in Table 11. Note that this is not a procurement plan, but rather an analysis of likely capital expenditure on CCE to match the needs of healthcare facility electrification presented above. Costs are illustrative, using an illustrative unit cost of EUR 2,500 (about USD 2,625) per electric freezer or refrigerator, and EUR 5,500 (about USD 5,775) per solar freezer or refrigerator, based on the list of WHO PQ-approved equipment. Actual costs will vary according to the units procured, when they are procured and other terms of the procurement.

[24] Source: Madagascar IEP Electrification Plan (2023).

Costs of walk-in cold rooms are not included below, as a) actual cost can vary widely depending on the needs for constructing; and b) all walk-in cold rooms described in Table 11 above are either repairable, not needed after DPEV's new warehouse construction, or not needed for distributing vaccines, as they are in regional facilities that do not house vaccines. The total estimated cost of equipment from Table 16 is USD 14.4 million.

Table 16. Baseline cold chain equipment deployment costs by year (illustrative costs)

Year needed	Electric Freezer (USD)	Electric Refrigerator (USD)	Solar Freezer (USD)	Solar Refrigerator (USD)
ASAP	$259,875	$501,375	$103,950	$5,792,325
2024	$2,625	$5,250	$0	$132,825
2025	$5,250	$5,250	$0	$537,075
2026	$0	$2,625	$0	$1,466,850
2027	$5,250	$5,250	$0	$392,700
2028	$0	$34,125	$0	$617,925
2029	$52,500	$34,125	$5,775	$3,210,900
2030	$15,750	$26,250	$0	$1,206,975

Sensitivity – Cold chain equipment procurement optimization

As mentioned above, this sensitivity examines the potential cost savings that would result from increased coordination between CCE procurement decisions and healthcare facility electrification. It assumes that at a national level 40 percent of the procurement attributed to SDD units in the baseline scenario presented above can instead be procured as less-expensive performant electric CCE, as this procurement will occur in facilities that have been sufficiently electrified through planned healthcare facility electrification and/or backup schemes. This shift of 40 percent of required solar freezer and refrigerator purchases to conventional electric unit purchases saves about USD 2.9 million compared to the baseline scenario, for a total cost of approximately USD 11.5 million.

Table 17. Cold chain equipment procurement optimization equipment deployment costs by year (illustrative costs)

Year needed	Electric Freezer (USD)	Electric Refrigerator (USD)	Solar Freezer (USD)	Solar Refrigerator (USD)	Hybrid System Electrification Costs (USD)	Off-Grid Systems Electrification Costs (USD)	Totals (USD)
ASAP	$278,775	$1,554,525	$62,370	$3,475,395			$5,092,290
By 2030	$82,425	$1,488,375	$3,465	$4,539,150	$7,004,852	$7,075,270	$20,193,537

Comparisons with the Powering Health Care study

A complementary report entitled *Market Assessment and Roadmap for the Electrification of Healthcare Facilities* by the Powering Health Care (PHC) team is under implementation with support from SEforALL in parallel with the IEP. The report has three key objectives:

1. Provide the Government of Madagascar (GoM) and key partners with data on the extent of the energy gaps within the healthcare sector, including non-electrified and semi-electrified healthcare facilities.
2. Provide strategic information and implementation guidelines needed to allocate the investments required to implement sustainable electrification of healthcare facilities.
3. Propose long-term sustainable options, including innovative finance models, for providing continuous and reliable electricity services.

The goal is to provide the impetus and solutions needed to increase investment in and the sustainability of healthcare facility electrification efforts to improve service quality in both CSBs and referral hospitals at the district level (CHRDs). While complementary, the objectives and scenarios for the PHC imply different assumptions from the IEP, notably with respect to design philosophy and scope. These lead to different but related outcomes for healthcare facility electrification.

The main recommendation from the PHC report is to implement a bottom-up approach where healthcare facilities are at the centre of an integrated programme to improve health services in general and electricity access in particular. The study also contains specific recommendations such as audits for CHRD electrification due to the wide variety of services proposed in these facilities. The differences in sizing for CSBs between the two studies are quite significant. The PHC roadmap estimates that the basic energy needs for a CSB1 is 5.5 kWh/day and for a CSB2 is 7.7 kWh/day.[25] In comparison the basic electrification proposal in the IEP for both CSB1 and CSB2 is set at just 1.120 Wh/day. Despite the difference in overall system sizing, it should be noted that the cost differences between the two approaches are proportional.

This range results from different design philosophies reflected in defining the power needs. The IEP approach is to supply critical facility equipment as defined for small health clinics in the USAID document *Powering Health: Load Calculation Examples* and using the information available about existing equipment on site at CSBs currently. This approach is applied to provide power for minimum critical health clinic equipment requirements for essential examinations, night birthing and vaccination functions, as described by USAID. The PHC roadmap philosophy takes a slightly broader view of the basic power needs of the whole healthcare facility, including electrification of housing facilities for healthcare workers and non-medical equipment to improve service quality and considering the digitalization approach of healthcare facilities of the World Bank DECIM project, all of which are reflected in the system sizes. The primary differences between the equipment units are outlined in the table below.

[25] Note that the PHC report provides a district sizing of CSB1 and CSB2 facilities, whereas the IEP uses an aggregated sizing for both CSB1 and CSB2.

The approach implemented by the government and partners in powering the healthcare facilities during the build-out of the facilities will need to balance the considerations above. If it is desired to add power to as many clinics as possible, stretching funding resources, one would tend toward a minimum-needs list to provide this. If one has funding available to optimize small clinics and maximize their funding, the larger systems outlined in the PHC report are desirable. Currently the approach taken by electrification programmes such as the World Bank's LEAD or DECIM programme have tended toward larger sizing in line with the objective of improving service quality (including digitalization), staff retention and overall sustainability of the electrification programme.

Table 18. IEP and PHC comparison for CSB1

Comparison of IEP and PHC Results for CSBs								
Equipment	IEP (Count)	PHC (Count)	Unit power (Watts)	IEP (Total Watts)	PHC (Total Watts)	Usage (Hours/day)	IEP (Wh/day)	PHC (Wh/day)
Lights	5	21	10	50	210	10*	380	2100
Radio	1	1	30	30	30	8	240	240
Microscope	1	1	10	10	10	2	20	20
Fridge for vaccine storage	1	1	60	60	60	8	480	480
Phone charging		5	5	0	25	4	0	100
Fan		1	80	0	80	10	0	800
Printer		1	100	0	100	1	0	100
Computer		1	120	0	120	4	0	480
Sterilizer		1	400	0	400	3.2	0	1280
Total	**8**	**33**		**150**	**1035**		**1120**	**5600**

* Two 20W exam lights run only 2 hours/day each.

Recommendations for Implementation

IEP analysis shows that meeting the full requirements for medical cold chain integrity and basic healthcare facility electrification will require USD 28.5 million in total investment by 2030 in the baseline case as shown in Table 19. This includes USD 14.4 million in cold chain equipment (CCE) investments (to acquire new equipment and replace equipment that has reached the end of its useful lifespan) and USD 14.1 million in investment in facility electrification, for both backup hybrid systems for already electrified facilities or facilities that are planned for electrification via a grid-based solution, and off-grid systems for more remote facilities. There is scope for some cost reduction for CCE to 2030 if it is possible to closely coordinate electrification (via sufficiently reliable and sustainable means) and CCEt procurement, as this would reduce reliance on more expensive solar direct-drive (SDD) refrigerators and allow for increased deployment of "standard" electric freezers and refrigerators. The analysis shows that shifting 40 percent of required procurements for solar refrigerators to electric equipment would generate overall cost savings of USD 2.9 million.

Table 19. Full requirements for medical cold chain integrity and basic healthcare facility electrification (IEP 2023)

Year needed	Electric Freezer (USD)	Electric Refrigerator (USD)	Solar Freezer (USD)	Solar Refrigerator (USD)	Hybrid System Electrification Costs (USD)	Off-Grid Systems Electrification Costs (USD)	Grand total
ASAP	$259,875	$501,375	$103,950	$5,792,325			
By 2030	$81,375	$112,875	$5,775	$7,565,250	$7,004,852	$7,075,270	**$ 28,502,922**
Total	**$341,250**	**$614,250**	**$109,725**	**$13,357,575**	**$7,004,852**	**$7,075,270**	

The medical cold chain analysis leads to several key takeaways that are summarized below:

- Generally, the medical CCE currently available and in use in Malagasy healthcare facilities is working well. Cold chain capacity is sufficient where it is available, particularly at the facility level, and can easily accommodate population growth and new vaccines. In areas that are difficult to reach during the rainy season, the immunization programme already adjusts the delivery frequency of vaccines, providing up to three months of vaccines when the facility is not accessible. As a cost savings opportunity, the MoH could adopt this adjusted delivery frequency to take advantage of the sufficient cold chain space and to reduce the effort for vaccine distribution.
- However, over 1,600 pieces of equipment are not functioning, and it will require a significant effort to decommission them and also to update the inventory. A decommissioning plan should be developed, financed and implemented to map out the country's approach to remove non-functional equipment from the system, considering best environmental practices, technical and safety considerations and documentation in assets management systems. The decommissioning plan should also plan for the future as equipment gets older and is no longer reliable, assuming a 10-year expected lifespan for CCE. By 2030, more than 1,500 currently functioning pieces of equipment will be more than 10 years old and should be assessed for functionality and possibly decommissioned. This goes together with a gap analysis and procurement strategy to replace older equipment. This will be particularly important to consider as the electricity grid expands and the more expensive solar CCE can be replaced as necessary with grid-dependent equipment.
- In addition, as the Government of Madagascar (GoM) works with donors and partners to upgrade and expand the cold chain system, additional areas to prioritize include:
    - Outdated equipment that is not performance, quality and safety (PQS) approved should be replaced (about 2 percent of all CCE). Equipment that was previously PQS approved but no longer has this approval can still be used if functioning but should be included in the medium- and long-term CCE replacement and expansion plan.
    - As additional funding becomes available for new equipment, prioritize replacing older equipment (10+ years), particularly the equipment that relies on gas/propane and is no longer PQS-approved. As the electricity grid expands and becomes more reliable, grid-based CCE is a dependable option that is less expensive than SDD and easier to maintain.
    - Consider moving some CCE from "underutilized" sites to "constrained utilization" sites, particularly at the district level, to alleviate some of the constraints. For example, if a district store or facility that falls in the underutilized category and has two or more pieces of CCE that are both working well, one of the pieces could be shifted to another location

that is considered "constrained" or has no CCE to alleviate the constraint and ensure availability of CCE.

- More than 500 facilities currently do not have functioning CCE, although some equipment is expected to be installed and other equipment is in the procurement process for 2024, with a focus on SDD equipment. To create a more reliable system, the MoH could consider procuring CCE for these remaining facilities to respond to the most immediate need, particularly in places with fast-growing populations and with a high need for vaccines. The cost of CCE that would be appropriate at facility or district level is between USD 2,500 and USD 6,000 per unit. This does not include maintenance costs, which vary by age and model.
- As the electricity grid expands and becomes more reliable, grid-based CCE can be procured, which is generally less expensive than SDD and easier to maintain. This would need to be closely coordinated with the electricity expansion plans and the next round of investment in CCE. Procurement of CCE typically happens every four to five years; by 2030 as the electricity grid has expanded, it will be an opportune moment to update the CCE inventory and electricity availability to develop a more nuanced CCE procurement strategy considering the electrification process. The government could shift from SDD to grid-based equipment in certain healthcare facilities that will have more reliable electricity at that point.
- The immunization programme should invest in its CCE maintenance system to ensure the longevity of the equipment.
- It is important to note that expanding CCE to new healthcare facilities must also consider the human resources required, which include demand creation and community mobilization.

The healthcare facility electrification analysis leads to several key takeaways that are summarized below:

- The IEP healthcare facility analysis is focused on planning for basic electrification of critical functions in healthcare facilities in the context of the ambitious objective of achieving universal access to energy in Madagascar by 2030. However, it should be noted that current design philosophies in Madagascar, as exemplified by the World Bank's LEAD and DECIM programmes and the SEforALL *Powering Healthcare Market Assessment and Roadmap*, have opted for significantly larger system sizing in line with the objective of improving service quality (including digitalization), staff retention and overall sustainability of the electrification programme.
- Facility Distribution and Energy Needs: Level 1 and level 2 basic health centres (CSB1 and CSB2) are the dominant healthcare facility types in terms of quantities, collectively representing a significant portion of the total healthcare facilities in Madagascar. They are located across the entire country, including in remote areas, and therefore account for a relatively high proportion of off-grid electrification solutions.
- Referral hospitals at the district level (CHRDs) stand out with substantial investments both on- and off-grid, indicating a strategic focus on integrating renewable and traditional energy sources to ensure both access and reliability of supply.

- The total energy requirement for hybrid solutions, i.e., backup systems for facilities already connected to a grid-based source of electricity- is substantially higher than that for off-grid solutions and represents roughly the same volume of investment as off-grid healthcare facility electrification does through 2030. This highlights the importance of reliable supply to healthcare facilities including those connected to the JIRAMA grid.
- The diverse range of facility types and needs highlights the importance of a multifaceted approach to addressing energy needs that balances budget requirements and objectives of an electrification programme that takes into account basic services, potential future improvements including digitization and the need for sustainable solutions that will vary across and within facility types. However, standardization of approaches to certain facility types such as CSBs, as suggested in the PHC roadmap study, could yield cost savings through economies of scale.

AGRICULTURE AND FISHERIES COLD CHAIN

Overview

The agriculture and food industries contribute approximately 43 percent of GDP to the Malagasy economy and employ 80 percent of the active population,[26] both formally and informally. Agricultural activities are primarily focused on subsistence agriculture that produce rice, cassava, potatoes, dry beans and maize. Crops produced in surplus of subsistence needs are sold locally in the domestic market. Small farmers are active in vegetable value chains because they provide regular cash flow as due to short crop cycles, limited capital requirements for cultivation, seed and fertilizer and intensification of cultivated areas in regions characterized by strong land pressure.[27]

Four types of market gardening archetypes are present in Madagascar: off-season on rice fields, off-season on hills (*tanety*) and seasonally dry stream beds (*baiboho*), permanent cultivation on exposed soi, and under orchard (in a more marginal way). Agriculture is not yet mechanized (apart from maize where mechanization is effective but remains low), and women are primarily responsible for cultivation, seeding, pest management and harvesting activities.[14] Agricultural production is characterized by a multitude of market participants: from production to consumption, products pass through intermediaries (collectors, wholesalers, transporters, retailers, processors, exporters), each of which has individual energy requirements.

The Integrated Energy Plan (IEP) is designed to evaluate both the status of cold chain technology that is used to refrigerate critical agricultural products in Madagascar today and the means and measures that are needed to expand access to cold chain technology in the future. Expansion of crops and food preservation through access to cold chain technology could significantly impact food security for products that are produced for domestic consumption. For those products that are produced specifically for export, improvement of agricultural cold chain technology could enhance export opportunities and bolster the economy. Nevertheless, in Sub-Saharan African countries, it has been shown that strict compliance with cold chain conditions and standards is difficult to practice locally because of social, cultural and economic barriers.[28] Due to market requirements, only refrigerated agricultural products intended for export to developed countries, or sold in domestic supermarkets, restaurants and hotels, are subject to compliance with formal national and international cold chain standards. As a result, the utilization of cold chain technologies and methods is not uniformly enforced or applied in the rural agricultural sector of Madagascar. The agricultural and fisheries value chains most closely linked to foreign consumption exhibit the highest emphasis on cold chain practices.

The agricultural cold chain analysis focuses on four critical agricultural value chains that will benefit from enhanced cold chain technology and mapping cold chain requirements along the

[26] FIDA 2021. Programme d'options stratégiques pour le pays 2022-2026.

[27] Fert 2012. Étude de la filière légumes sur les Hautes Terres de Madagascar.

[28] Rutta, 2022. Understanding barriers impeding the deployment of Solar Powered Cold Storage Technologies for postharvest tomato losses reduction: Insight from small-scale farmers in Tanzania.

value chains together with access to energy services, access to cold chain technology and the status of refrigeration along the value chain. The analysis includes an assessment of specific technology used, the volume of products that benefit from access to cold chain services and a gap analysis to identify specific deficits and opportunities that could profit Malagasy producers in the future. This includes an assessment of refrigerated transport, refrigerated cold storage and cold chain equipment at distribution centres. It also includes an evaluation of the existing technology stack across each selected value chain and an assessment of cooling needs and availability, efficiency and affordability of sustainable cooling technologies.

Value chains examined

Through the IEP inception process, dairy, fisheries, potatoes and tomatoes were selected and validated for analysis. The four value chains proposed were agreed to by the IEP stakeholders including Sustainable Energy for All (SEforALL) and the Ministry of Agriculture, Fisheries and Livestock (MINAE), among other government entities, and were selected based on: (1) the potential impact of improved cold storage; (2) sectoral priorities; and (3) their potential to contribute to improved income generating or nutritional outcomes. An overview of each value chain is presented in the section below and is followed by a summary of the field mission undertaken by the analysis team during the execution of this analysis.

Figure 33. Potatoes stored at a local Malagasy market

(Source: KODJOGBE Guy)

Potato

Potatoes are grown primarily in the Anamalanga, Itasy and Matsiatra Ambony regions,[29] which are heterogeneous in terms of agroeconomic potential, production, cropping system and development potential. Potatoes are harvested throughout January and February. Figure 33 shows these four major projection areas, while Figure 35 shows the distribution of potato harvest yield across the regions and districts of Madagascar.

Potatoes are one of the most important crops in volume, with a production volume of approximately 500,000 tons/year;[2], 251,000 tons (FAOSTAT 2023) were harvested in 2023 (see Table 13). Economically profitable, potatoes are cultivated for individual consumption in the lean season when rice is not plentiful. Potato production includes multiple actors (including MINAE, wholesalers, retailers and others) and is relatively well organized. Production is currently in crisis due to the resurgence of several diseases (mildew, bacteriosis and others) and a problem with access to healthy seminal

[29] Filière Capagne, 2021-2022, Service Regional, Ministere De L'Agriculture, et de L'Elevage ; The Ministry of Agriculture also reports that Vakinankaratra produces potatoes.

stock. This situation disrupts the supply of local and external markets both in terms of quality and regularity.[25]

Madagascar is struggling to deal with its post-harvest handling challenges. During field mission interviewers with MINAE staff, growers and traders it was noted that their perceptions on post-harvest losses on the tomato and potato values chains are higher (estimated at 60 percent) at the farmer level than at the wholesaler (10percent) or retailer levels (2 percent). These rates of post-harvest losses at the farm level are due to the difficulties that producers encounter (especially in isolated areas) in transporting products to markets or urban areas. In addition, market traders stock up on potatoes and tomatoes according to product demand, season and market days. The rates of post-harvest losses at the farm level are reported to be due to the difficulties that producers encounter (especially in isolated areas) in transporting products to markets and/or urban areas.

Most farmers harvest their potatoes a day before their local market day and transport them to market in large sacks (see Figure 33) or the products are bought at the farm by the market collectors at relatively low prices (for example MGA 700,000 per ton). Based on the field mission, many small farms harvest an average of only a few kilograms of potatoes a day during the harvest months.

Potatoes in Madagascar are largely stored on site. On site (in situ) storage means delaying harvest until the crop is ready to be sold. This can be done (with certain types of tuber crops) in the field where the crop is grown. However, when this is the case, the crop can be more easily exposed to disease and pests. Simple traditional storage structures are also used for storing the horticultural produce for the local market. These facilities use a passive cooling method of using natural or prevailing winds for air movement to create the desired cooling. The zero-energy cool chamber (ZECC),[30] charcoal cooler and storage structure (made with traditional material like straw roofs and water-repellent bricks) are common examples of this type of storage structure.

Several organizations are involved in potato production in Madagascar, for example the CEFFEL organization in Vakinakaratra produces certified potato seeds for farmers and uses simple traditional storage structures based on passive evaporative cooling systems such as the charcoal cooler. In addition, in Amoron'I Mania, the Food and Agriculture Organization (FAO) is providing a women-led vegetable growers association with training on fruits and vegetable processing, mainly on drying and juice production. Similarly, LECOFRUIT, a company that exports fruits and vegetables to Europe or China, transports potatoes using trucks at ambient temperature; no cold storage is used during transport. However, their products are stored in modern cold rooms once they arrive in their warehouses, with temperature control to respect the standards at destination.

Tomato

Tomatoes are grown primarily in the Anamalanga and Itasy regions.[31] They are harvested throughout September and October. The ideal harvest consists of washing tomatoes and

[30] See - https://srrweb.cc.lehigh.edu/app/ZECC

[31] The Ministry of Agriculture also reports that tomatoes are produced in Alaotra Mangoro.

packaging them, followed by cooling to either 20°C for ripening, or to 13°C for storage, in 90 percent–100 percent relative humidity (RH) conditions.

An estimated 100,000 tons of tomatoes are grown annually in Madagascar, with well-organized producers, particularly in the Itasy region. Tomatoes are a profitable but fragile product susceptible to diseases, weather and bruising in transport. Production, harvesting and transportation to market are not always well managed by farmer-producers, which can lead to high levels of losses and low sales revenue.[25]

Like potatoes, tomato post-harvest losses are a challenge in Madagascar. At local markets, wholesalers store their tomatoes in ambient temperature rooms and place their produce on fresh leaves to maintain their freshness. There is no storage solution for tomatoes in Madagascar at the present time. Note the similarity in the areas of potato and tomato production, and since the growing periods are not the same (outside off-season periods), there exists the potential to use the same cold storage solution for both crops.

Figure 34. Potato and tomato production areas in Madagascar

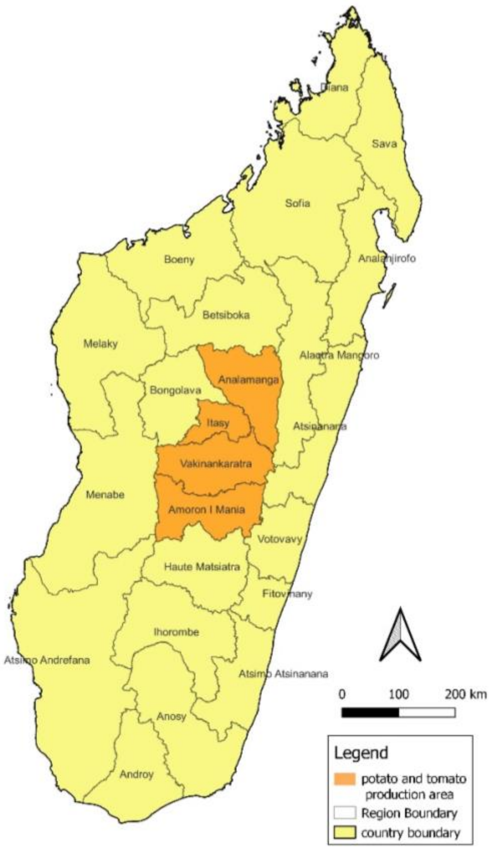


Figure 35. Distribution of potato yield in Madagascar (Source: FAO Agri Maps)

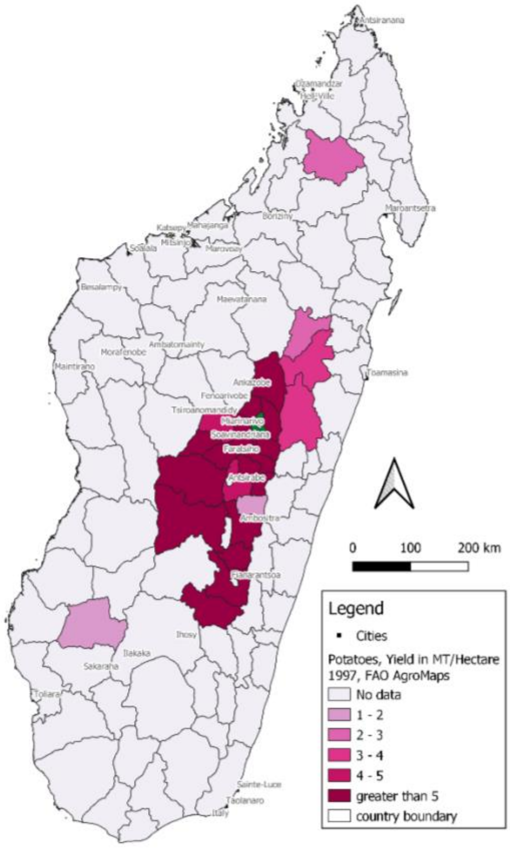


Table 20 presents a summary of fruit, vegetables, spices, grains and legumes produced in Madagascar, to benchmark the harvest quantities of potatoes and tomatoes in the country.

Table 20. Major crops produced in Madagascar (Source for crop harvest tonnes: FAOSTAT 2023)

Crops and processed crops	Quantity Harvested (tonnes)	Cold Storage Requirements
Avocados	27,309	Optional to extend storage life.l 5°C–12°C 85–95% RH to prevent ripening, 3-5°C if pre-conditioned
Bananas	382,196	Ripening in 100 ppm Ethylene at 14-18°C, 90-95% RH
Eggplants	1,780	10-12°C, 90-95% RH
Groundnuts, excluding shelled	62,934	10°C, 65% RH
Sweet potatoes	1,143,320	Cure 29°C 4-7 days, 90-97% RH Store 14°C 90% RH
Taro	234,947	7–10°C, 80-95% RH
Tomatoes	40,863	13°C, 90-95% RH
Other vegetables, fresh NEC.	374,204	5–8°C is general warehouse temperature, but some cold-sensitive items, like bananas, cannot be stored at temperatures that low, so warehouse temperature mapping is used to identify higher temperature zones up to 13°C for these items.
Peaches and nectarines	10,832	-1°C–0°C, at 90-95% RH with 15 m//min airflow
Pears	1,435	-1°C, 90-94% RH.
Mangoes, guavas and mangosteens	299,285	10–13°C, 90% RH for mature green fruit 7–8°C, 90% RH for ripe fruit 20–23°V 90% RH for ripening
Peas, green	1,368	0°C, 95-98% RH. Do not allow to go above 2°C during storage
Pepper (Piper spp.), Raw	5,282	7°C, 90-95% RH. May go as high as 10°C if packaged in plastic wrap
Pineapples	85,219	7-12°C, 85-95% RH at color break point 7°C for ripe fruit
Potatoes	251,257	Optional to optimize storage life: 15°C for 2 weeks curing, 80-100% RH with air exchange. 2-3°C for extreme life 4-5°C for seed potatoes 7-10°C for fresh consumption 10-15°C for frying 15-20°C for chipping

Fisheries

The fisheries industry has significant refrigeration,[32] and cold chain needs and export potential. The greatest concentration of fisheries (65 percent) is found in the northwestern part of Madagascar between Cap Saint Sébastien in the north and the tip of Angadoka in the south as well as Cap d'Amparafaka in the north and Nosy Voalavo in the south[33] – see Figure 36. The types of fish and the methods of harvesting have significant implications for cold chain strategies. Specifically, maritime traditional fishing is performed almost entirely along the Malagasy coast, including in extremely remote regions, whereas maritime industrial fishing is concentrated in larger port cities that are more likely to benefit from refrigeration, ice making and other pre-cooling capability. Similarly, while it's not a major factor in national production, inland fishing in lakes and rivers exhibits more seasonality, which is more vulnerable to access limitations and cold chain interruptions. Moreover, mariculture and aquiculture can be somewhat concentrated in zones with cold chain infrastructure access, although this is not universally practiced in Madagascar. Table 21 illustrates 2022 fishery production in tons by fishery type.

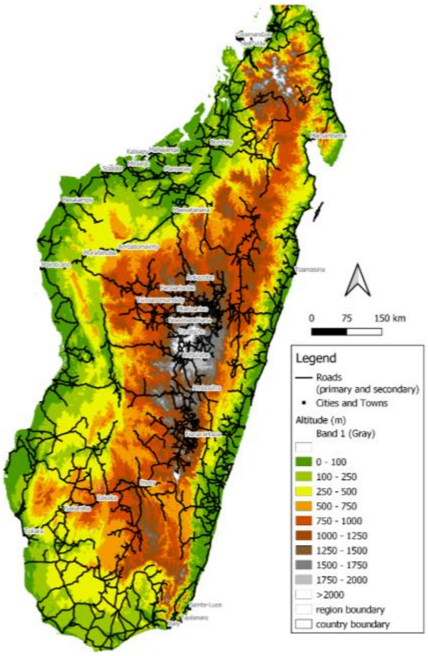
Table 21. Madagascar: fishery production in tons
(Source: Fisheries Ministry 2022)

Fishery type	Production in tons (2022)
Maritime industrial fishing	24,169
Maritime traditional fishing	87,595
Inland traditional fishing	10,285
Mariculture (Ocean fish farming)	23,023
Aquaculture (Freshwater fish farming)	2,098
TOTAL	**147,364**

[32] See – Distant water industrial fishing in developing countries: A case study of Madagascar (biorxiv.org) for more background.
[33] Trade Map, 2022. trademap.org Statistiques du commerce pour le développement international des entreprises Données de commerce mensuelles, trimestrielles et annuelles. Importations et exportations en valeurs, volumes, taux de croissance, parts de marchés, etc.

Figure 36. Key production areas of fisheries (Source: Trade Map 2022)

Figure 37. Roads, terrain, and major cities and towns.



According to interviews conducted during the field mission, seafood is generally transported in refrigerated vehicles. At local markets, seafood is sprinkled with ice water regularly and placed on leaves for preservation. The lack of adequate cold chains has a direct impact on post-harvest losses. For example, the average cumulative crab mortality cumulative rate is 32 percent, and this increases to 40–50 percent during the rainy season. Post-harvest losses for crabs alone are estimated to be USD 4.7 million per year.[30] The main causes of post-harvest losses are compression, choking, dehydration, starvation or bacterial contamination due to the presence of dead crabs. In most cases, losses are due to poor handling practices on the part of collectors. Since the global analysis of the sector conducted in 2012, SmartFish has made a significant contribution to the mangrove crab sector, particularly on the issue of post-harvest losses by promoting the adoption of new handling, storage and transport techniques. A community aquaculture pilot project was also initiated, as well as support for the complete rehabilitation of three important markets in Morondava, Antsohihy and Ambanja[34]

As can be seen in Figure 36, the major cities and towns in Madagascar are found along the coasts (mainly in the south and north), as well as in the central highlands. While road networks do connect the coasts to the central highlands, as noted in the cold chain challenge section, these important arteries are greatly degraded by seasonal precipitation, insufficient infrastructure and difficult terrain making it challenging to ensure cold chain integrity – particularly for fisheries. Note the difficulty and length of the trip a fish caught in Toliara must transit to arrive at a market in Antananarivo, a journey of over 700 kilometers.

[34] For more information see - https://www.commissionoceanindien.org/smartfish-appuie-madagascar-pour-une-exploitation-rationnelle-et-durable-du-crabe-de-mangrove/

Fish losses are often seasonal, occurring during times of glut catches or during the rainy season when traditional processing methods are less effective. Losses are also associated with certain species of fish, types of fishing or processing methods. They may also be occurring in particular types of locations e.g., remote areas where services and infrastructure are poor. Seafood product post-harvest losses, according to perceptions of the Ministry of Fisheries staff and traders, can be estimated at approximately 80 percent.[35] However, fish market traders do not record losses, and unsold items are self consumed as dried or fried fish.

A number of initiatives aiming to reduce post-harvest loss for fish and seafood products have been or will be piloted by the Government of Madagascar (GoM) and its development partners.

GIZ, through the PrAda[36] project that has undertaken some measures and interventions within the Malagasy fisheries sector, including:

- Study on the fish market equipment in Ambovombe
- Testing of offshore storage techniques and lobster transport conditions
- Installation of 10 fishing Système d'Alerte Précoce (SAP) panels
- Training of fishermen on new fishing techniques (longlines, jigs)

In 2021, GIZ also installed an ice production unit in Ambovombe and rehabilitated cold rooms in Ikotoala and Faux Cap.[37] Figure 37 provides a map of the cold storage activities of GIZ-supported fisheries in southern Madagascar. The GIZ 'More fish, more work' project is also ongoing and advises small and medium-sized businesses on sustainable fish production and processing. This creates jobs and income-generating opportunities in the value chain. Innovative production methods cut costs and reduce after-catch losses.

In addition, the World Food Programme (WFP) is also active in the fisheries value chain in Madagascar. The initiatives include:

- Ambovombe cold room pilot project – fishermen pay for cold-room services delivered through refurbished 20-foot container cold rooms, expected to have been operational in September 2023
- Talakiba cold room for fish products powered by a mini-grid
- Southerm Madagascar Africagreen Tec award for the installation of phase charge material (PCM) cold rooms

[35] SMART Fiche 17. PROGRAMME FOR THE IMPLEMENTATION OF A REGIONAL FISHERIES STRATEGY FOR THE EASTERN AND SOUTHERN AFRICA - INDIAN OCEAN REGION. Reducing postharvest fish losses for improved food security.

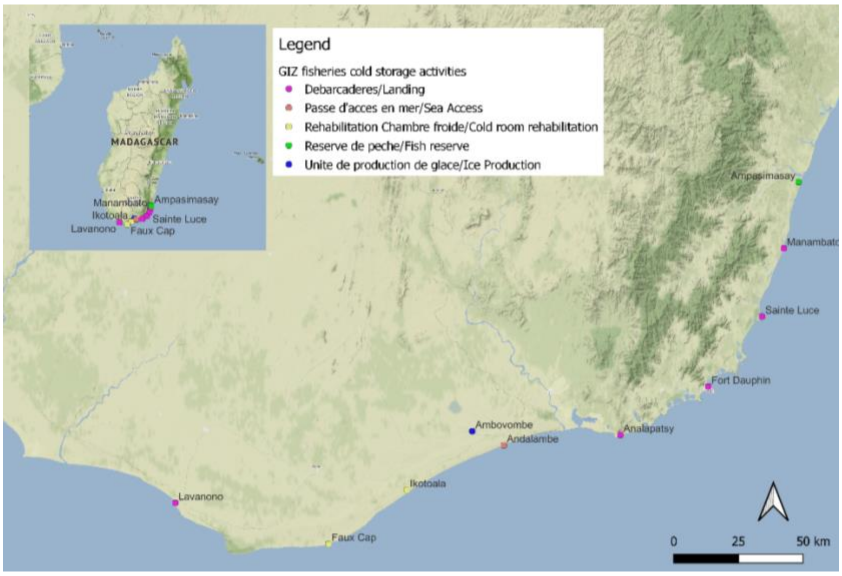
[36] Fiche Technique Chaîne de Valeur Pêche Projet Adaptation des chaînes de valeurs, agricoles au changement climatique – PrAda, Novembre 2020.

[37] Derived from GIZ 2021 activities planning data received.

Other initiatives include:

- Aquatic Service, an NGO, has installed cold rooms and freezing tunnels for fish storage
- UNDP has installed a cold room for seafood products in the Cavanono district of Beloha
- In November 2023, FAO had plans to install a fish conditioning centre and an ice block machine in southern Madagascar
- SWiofish2,[38] the South West Indian Ocean Fisheries Governance and Shared Growth Project, is also active in Madagascar.

Figure 38. Cold storage activities of GIZ-supported fisheries (GIZ 2023)



Dairy

Dairy production is important for nutritional value and the potential value for domestic consumption. Madagascar produces nearly 100 million liters of milk per year: 67 million liters come from foreign breeds of dairy cows and 33 million from local breeds of cows.[39] Apart from agro-industrial transformation, the dairy sector brings together nearly 80,000 operators, 90 percent of whom are producers. The production is not generally self consumed (less than 4 percent of the quantities produced are self consumed) but is mainly intended to be sold: 65 percent of production is sold to collectors and sub-collectors, 18 percent to cheese and yoghurt , 12 percent to grocery stores and hotels and around 5 percent in direct sales to consumers.[40] In Madagascar, most dairy production is carried out in a region of the Highlands called "the dairy triangle" located between the towns of Manjakandriana, to the east, Tsiroanomandidy, to the west and Ambalavao, to the south – see Figure 39. Table 22 presents a comparison of dairy production in various regions.

[38] https://www.swiofish2.mg/swiofish-2/

[39] Présentation de la Coopérative FI et de la Mutuelle d'épargne et de crédit : 2015.

[40] Bélières & Lançon, 2020. Etude diagnostic relative au potentiel de croissance de la chaîne de valeur lait et de ses produits dérivés (Hautes Terres—Madagascar). CIRAD. https://agritrop.cirad.fr/595207/

Figure 39. Dairy production areas in Madagascar (2023)

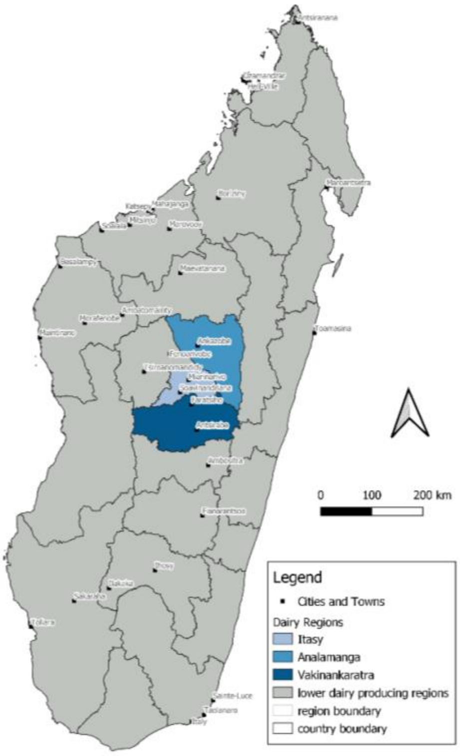


Table 22. Dairy production per area in liters/year in Madagascar (DRAEP 2018)

Dairy Producing Areas (Districts)	Percent of Dairy Production
Antsirabe I	10
Antsirabe II	35
Betafo	35
Faratsiho	10
Other areas	10

Most Malagasy dairy companies and organizations, as observed during the field mission, use tanks for collecting the milk at the farm level and reducing its temperature. Tank capacities vary from 200 liters to 800 liters according to the size or production capacity of the companies. Sometimes the tanks are located far from the farmers' houses or sites. The milk is often made into cheese or yoghurt. Small and medium-sized milk processing companies (such as ROVA, ECOFARM, YAJA and MISOA) find it difficult to store their products in modern cold rooms with a temperature control system because of the high cost of this type of equipment. The five small and medium-sized companies visited during the field mission use cold rooms or simple cellars installed in the basement of their facilities for storage purposes, while also using simple commercial refrigerators for storing dairy products.

For smaller and medium-scale industrial dairy manufacturers, such as the CCC company, there exists a substantial risk of incurring processing losses. These may escalate to as high as 80 percent at the farmer level and 30 to 40 percent at the processing stage according to stakeholders' perceptions, primarily attributable to prolonged storage-related disruptions.

Methodology Summary

Data collection and stakeholder interviews

A field mission to Madagascar took place from 29 May 2023 to 10 June 2023 for the purpose of collecting primary and secondary data on the agricultural cold chain for the four value chains selected. A total of 34 meetings and visits were conducted including with relevant ministries, businesses, farmers' associations and international organizations. The mission included meetings in Antananarivo and also travel to regions where the products under evaluation are grown and harvested including Vakinankaratra, Itasy and Amoron'I Mania. The field mission validated assumptions that infrastructure (electrical and roads) was a key impediment to cold chain development. A summary of key observations from the mission is presented below.

Results of the Field Study

According to the World Food Programme (WFP), there is a clear and pressing need for the development of a cold chain infrastructure within the agricultural sector in Madagascar, particularly for fisheries, beef, dairy products and processed fruits and vegetables. The medium-term strategy involves harnessing solar energy to power cold storage facilities, while the long-term plan envisions the utilization of hydroelectric energy for increased efficiency and effectiveness.

The Food and Agriculture Organization (FAO) took concrete steps to address this issue with plans to set up a fish packing centre and an ice block machine in November 2023. This initiative aims to assist traditional fishermen in transporting their catch from the sea to their homes or collection sites. Given that these fishermen live five to six kilometers from the coast, the lack of proper transportation infrastructure makes this support crucial for their livelihoods.

Multiple ongoing and prospective projects are dedicated to promoting the cold chain in Madagascar, with organizations like FAO, UNDP and the NGO Aquatic Service actively involved. Notably, the NGO Aquatic Service already has cold rooms and freezing tunnels in the fish market. Other contributors to these cold chain initiatives include the Catholic Relief Services (CRS) and the International Fund for Agricultural Development (IFAD), with most projects concentrated in the regions of Ambovombe, Tiluar, Beloha and Majunga.

For fresh vegetables and fruits, typically cultivated by small-scale producers, small refrigerators are commonly used. Some of these refrigerators operate on solar energy, while others rely on JIRAMA or generator electricity sources. Interestingly, the preservation of lychee, a significant product in Tamatave, involves the use of sulphur.

The Ministry of Fisheries in Madagascar oversees several key players in the seafood industry within the country. Two notable organizations, the Centre for the Development of Fishery Products (CDPHM) and the Société des Pêches Capture Accessoires, collaborate closely with small-scale fishermen to gather and transport seafood to their processing and marketing centres. These two companies contribute to the annual production of approximately 5,000 to 10,000 metric tons of seafood products.

The SWIOFISH2 project plays a pivotal role in Madagascar's fisheries sector. The project is dedicated to enhancing the cold chain infrastructure in fisheries, aiming to establish cold storage facilities in eight regions across the country. During the first phase of implementation, three regions – Melaky, Diana and Analanjirofo – were impacted. Subsequently, the project expanded to include five more areas in its second phase: Menabe, Atsimo Andrefoama, Atsimo Antsimana, Anjoy and Osoemy. This ambitious initiative not only supports the preservation of seafood quality but also contributes to the overall growth and sustainability of Madagascar's thriving fisheries industry.

In Tamatave, the company Refrigepeche Est engages in industrial fishing, specializing in pelagic fish such as tuna and other similar species, with an annual production ranging from 128 to 340 metric tons. Impressively, 90 percent of its output is earmarked for export to European markets. However, the operations of Refrigepeche Est are currently facing a setback as they have been forced to suspend activities due to a shortage of fuel supply, a matter overseen by the Ministry of Fisheries.

In Morondava, SOPEMO has a notable presence, boasting three decades of experience in semi-industrial seafood production. It generates an annual production volume ranging from 134 to 340 metric tons of groundfish. The entirety of SOPEMO's production is geared towards export, with European and Chinese markets being the primary destinations for their high-quality seafood products.

However, challenges persist, particularly for larger fisheries enterprises like Nanda Seafood, which find the installation of solar cold rooms to be prohibitively expensive due to a lack of financial assistance and affordable credit options. In cases where credit is available, the high-interest rates, ranging from 15 percent to 20 percent, pose additional barriers to investment in the cold chain infrastructure, underscoring the need for more accessible financing mechanisms to support the growth of this vital sector in Madagascar.

The Ministry of Agriculture staff identified several significant constraints hindering the development of a cold chain infrastructure for agricultural products. These include the lack of professionalism within the value chains, with growers often failing to adhere to delivery contracts with their buyers. The high cost associated with cold chain equipment (CCE), coupled with challenges in accessing markets, further complicates the situation. Additionally, there is a notable issue with the local customer demand, which often prioritizes quantity over the quality of commodities and fresh produce such as vegetables and fruit instead of refrigerated productsConsequently, the existing cold chain systems primarily cater to certified products intended for affluent consumers, highlighting the need to address these constraints to ensure more equitable access and broader benefits within the agricultural sector.

Women's associations often require financial contributions from their members, typically amounting to MGA 500 per day for maintenance equipment fees and MGA 2,500 per week for the social fund, which covers expenses related to illness, marriage and funerals. Support from organizations like FAO and UNICEF has been instrumental in empowering these women, offering training in various aspects such as production techniques for cassava and food products, fruit processing methods including candied fruit and fruit paste, and the conversion of sweet potatoes and potatoes into flour. Additionally, UNICEF has provided training in entrepreneurial culture, savings, credit management and nutritional education, accompanied by culinary demonstrations.

Despite their resilience and determination, women's organizations in Madagascar face significant challenges. Access to land remains a persistent issue, as women encounter more obstacles in obtaining land than men. Educational and business training opportunities for women are limited, and there is a notable lack of female representation in extension services. Access to finance is also a considerable hurdle, as many women lack capital and often require their husbands' approval to apply for loans. Inequitable inheritance laws place women seventh in line for their husband's property, following children, parents, siblings and other relatives, further compounding land-ownership challenges for women in Madagascar. Consequently, there is a pressing need for measures to address these challenges and provide women with opportunities to enhance their livelihoods and economic sustainability for themselves and their families.

Other observations from the field mission include:

- Lack of electrification is a critical and urgent issue. JIRAMA's grid does not cover large areas in the country, particularly in rural areas. The absence of electricity, repetitive power outages and poor power quality prevent farmers and small industries from producing large quantities of products and exacerbate storage issues. Anecdotally, large companies such as the supermarket Super U reported in June 2023 that EUR 200,000 of fresh products were spoiled and had to be discarded because of an extended power outage.
- Poor quality roads, as is noted in the Accessibility in Madagascar section, are a major barrier for safe and effective transport of perishable products from rural areas to urban areas. Some supermarkets like Super U use airplanes to transport perishable products from Tamatave to Antananarivo, adding to the cost of the products.
- From a total of 22 women interviewed during the field mission, just two had a formal education and have their own processing companies with more than five years experiences. One has a cold chain system for seafood products exported to Europe (Manda Sea Food). Six are vegetable growers from rural regions of Amoron'i Mania and are not educated, while all others work for the government.
- An agricultural women growers' organization at Amoron'I Mania, while not formalized, was created two years ago through an FAO project. They reported receiving inputs such as high-quality seeds, technical advice and training in fruit and vegetable processing.
- During field mission interviewers with staff and growers from the Ministry of Agriculture and Livestock (MINAE), it was noted that -losses on the tomato and potato value chains are higher (estimated at 60 percent) at the farmer level than at the levels of wholesalers (10 percent) or retailers (2 percent). These rates of post-harvest losses at the farm level are due to the difficulties that producers encounter (especially in isolated areas) in transporting products to markets or urban areas. In addition, market traders stock up on potatoes and tomatoes according to product demand, season and market days.
- It was noted that there is a huge need for good quality cold chain equipment or materials (most equipment used comes from China and is not good quality) with a temperature-control system. Only the big companies like LECOFRUIT, SOCOLAIT, supermarkets and some high-end hotels use modern cold rooms for preserving food. This is because of the high costs of those materials that are more than companies and growers can afford.
- Small and medium-sized industries and producer organizations reported encountering issues selling their products due to a lack of customers and market information. At Itasy more than 60 percent of tomatoes[41] produced are lost because of lack of proper post-harvest handling including lack of cold chain, poor quality roads to transport the products

[41] Interview with Ministry of industry staff at Itasy 9/06/2023.

to urban sites and the lack or difficulties of accessing conservation and processing equipment.

Among others, some government institutions and donor-supported initiatives[42] that are underway to support agricultural value chains, include:

- PTASO – Agro-industrial Transformation Zone Development Project in the South-West Region of Madagascar: promotion of agricultural value chains (CVA) such as rice, cape peas, corn, agricultural products, fisheries and small ruminants through the development of infrastructure and the implementation of various incentives for the private sector for industrial processing and marketing.
- CABIZ – Agribusiness Support Centres and the Guichet Agricole: Providing services for farmers. Strengthening training on agricultural in rural communities is underway in four regions (Atsinanana, Analamanga, Amoron'i Mania and Menabe).
- CHALLENGES (2018–2028) – Development of inclusive sectors: infrastructure development post-harvest and market access to reduce post-harvest losses and improve market access, competitiveness and producer income.
- ODOP – One District One Product concept: The aim of this programme is to promote products from regions in Madagascar.
- ODOF – One District One Factory approach: The project is an initiative to change the economy in Madagascar from one that is dependent on the import and export of raw materials to one that is focused on value addition and the export of processed goods.
- FDA – Le Fonds de Développement Agricole: Consulting, information and training in the technical, legal, organization, standards as well as financing of processing equipment.
- Agricultural census (completed in 2025 potentially).

Post-harvest storage facilities archetypes

In 2011 FAO reported that in Sub-Saharan Africa, the post-harvest losses on different agri-foods value chains are estimated to be around 37 percent, i.e., 20–170 kg/year of food per capita is lost or wasted.[43] In 2020, FAO reported that up to 40–50 percent of produce perishes before reaching the end customer, largely due to a lack of viable cold chain solutions. Significant quantities of products rot in producing areas in Madagascar, due to a lack of distribution channels and effective marketing. Strengthening the establishment of conservation and transformation structures would reduce these losses but would also bring added value to local production. Post-harvest storage facilities play a crucial role in preserving agricultural produce and minimizing post-harvest losses. These facilities can be categorized into different levels based on their scale and infrastructure requirements: 1) on-farm storage, 2) regional community storage, 3) urban centralized storage, and 4) retail storage. Table 23 describes the common levels of post-harvest storage facilities, from

[42] National Roadmap for the Transformation of Food Systems to Support the Achievement of the Sustainable Development Agenda 2030. April 2022.

[43] FAO. 2011a. Global food losses and food waste – extent, causes and prevention,by J.Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijkand A. Meybeck.Rome. http://www.fao.org/docrep/014/mb060e/mb060e00.pdf

farm to retail, along with equipment recommendations, basic layout, energy and other infrastructure needs.

Table 23. Common levels of post-harvest storage facilities

	On Farm Storage	Regional Community Storage	Urban Centralized Storage	Retail Storage
Definition:	On-farm storage facilities are located directly at the agricultural production site and are typically used for short-term storage. They are essential for preserving harvested crops before transportation to larger storage facilities.	Regional community storage facilities serve a larger population within a specific geographic area, allowing farmers to storetheir produce collectively while waiting for a period when product prices rise on the market. These facilities are typically managed by cooperatives or farmer groups.	Urban centralized storage facilities are in larger towns or cities and serve as major hubs for storing agricultural produce. They handle a significant volume of produce from multiple farms and supply it to various retailers or processors.	Retail storage facilities are usually in urban areas and cater to the final stages of the supply chain, including supermarkets, grocery stores, or fresh produce markets. These facilitiesfocus on maintaining product quality and ensuring attractive presentation to customers.
Common types of storage and bulk storage practices:	Simple storage structures like bins or silos made of locally available materials such as bamboo, wood, or mud can be used for storing grains, tubers, or fruits.	Warehouses are larger storage facilities with proper infrastructure for bulk storage of grains, tubers, or other non-perishable crops. They may have separate sections for different farmers or produce.	Sophisticated cold storage warehouses equipped with multiple refrigeration units, temperature control mechanisms and sorting and grading sections.	Walk-in cold rooms are smaller-scale cold storage facilities within retail stores for maintaining the freshness of perishable produce.
Cold Storage Practices:	Cold Storage – for perishable crops, such as fruits and vegetables, small-scale refrigeration units, such as cool rooms or walk-in cold storage, can be used to maintain low temperatures and preserve quality.	Cold Rooms – Community-level cold storage facilities equipped with refrigeration units can store perishable crops fo longer periods, maintaining freshness and reducing spoilage.	Sophisticated cold storage warehouses are required as described above.	Display Shelves and Counters – Designed to showcase fresh fruits, vegetables, and other agricultural products, these storage areas may include refrigerated sections for specific items.

Basic Layout of Cold Chain:	The layout can vary based on the available space and the type of crops being stored. It should ensure proper ventilation, protection from pestsand easy access for loading and unloading.	Community storage facilities require adequate space for storing larger quantities of produce according to product availability. The layout should include appropriate ventilation, pest-control measures, loading docks, and sorting areas.	Centralized storage facilities require a well-designed layout to handle high volumes of produce efficiently. This includes separate storage areas for different crops, loading and unloading bays, quality control sections, and administrative offices.	Retail storage facilities require organized and visually appealing displays to attract customers. The layout should include shelving, refrigeration units and proper lighting to enhance product visibility.
Equipment Recommendations:	Basic equipment may include storage containers (bins or silos), temperature- and humidity-monitoring devices and simple cooling systems (for cold storage).	Warehouse shelving or pallet racking, mechanical handling equipment (forklifts or hand carts), temperature and humidity monitoring systems and refrigeration units for cold storage.	Advanced temperature and humidity control systems, mechanical handling equipment (conveyors, elevators), computerized inventory management systems, grading and sorting machines, and specialized refrigeration units.	Refrigerated display cases, storage racks, temperature monitoring devices and lighting fixtures.
Energy Needs:	On-farm storage energy needs can be met by a variety of sources including electricity, solar power, or biomass-based systems, depending on the availability and affordability of resources in the specific location.	Community storage facilities typically require a reliable electricity supply or alternative power sources like solar energy to operate refrigeration systems and provide lighting.	Centralized storage facilities need a reliable electricity supply, often backed up by generators, to support the operation of various mechanical and refrigeration systems.	Retail storage facilities primarily rely on electricity for their refrigeration and lighting requirements.
Cold Chain Link Needs:	Access to means of transporting from farm storage to markets or to a central storage facility without spoilage, whether owned by the farmer or sent by a distributor or storage facility.	Access to means of storage of products until a favourable sales period and temperature-controlled transportation to collect from farmers who cannot deliver produce and to transport either to area markets or to	Access to means of transportation and temperature-controlled transportation to collect from farmers who cannot deliver produce and to transport either to markets or to food processors.	Access to means of transportation and temperature-controlled transportation to collect from central storage facilities without temperature rise that would increase the load on the retailer's

		food processors or to the urban centralized storage as described below.		refrigeration equipment.

Cold chain equipment

This section provides an indicative overview of the types of cooling technologies being used for the value chains and how they differ by level (farm to retail). Given the current general lack of off-grid cooling solutions in Madagascar, the cold chain equipment presented below illustrates what is available in the region that could be brought into Madagascar.

Refrigeration equipment for curing and storing vegetation

Equipment options for refrigeration are significant, as are price differences. For refrigeration, the professional standard is commercial walk-in refrigeration equipment, but this will vary in cost and quality, depending on the source. There are two basic components to refrigeration equipment for curing and storing vegetation: the insulated box and the refrigeration equipment. Typically, insulated boxes are made with steel-clad polystyrene or polyurethane foam insulation, and some come in panels that can be cut and assembled with carpentry tools. Better-quality insulated boxes typically are formed with polyurethane foam between the steel outer skins in standard widths and heights that interlock with hook-and-pin camming mechanisms that allow the panels to be assembled with a single wrench tool very quickly. This also allows for the option to disassemble and change panel location a few times over the lifespan of the system. The steel must be coated to allow proper sanitation and cleaning to meet food-safe standards, while preventing corrosion of the steel. Doors are designed to fit these containers that are filled with the same insulation material, and typically provide a locking mechanism that can be released from inside the box by anyone who is inside when the door is closed. The release is designed to work even if the outside latch has been padlocked. The figures below provide illustrative examples of insulated boxes as they are being installed on site.

Figure 40. Insulated box panel assembly

Figure 41. Insulated box with small commercial standalone solar installation above it

The refrigeration equipment is the other main component of cold chain equipment for curing and storing vegetation. While the foam panels described above for the insulated box are produced in several countries in Sub-Saharan Africa and that capability is expanding, high-quality condensing and evaporating equipment is generally imported. Piping and charging the equipment is then done at the assembly site. Generally, the efficiency of higher-quality equipment is higher than that of inexpensive equipment, producing more cooling watts per watt of electrical power consumed. Additionally, modern equipment is increasingly designed to work with more environmentally friendly refrigerants.

Alternative or improvised condensing and evaporating equipment is often used to limit capital outlays of more expensive commercial grade imported equipment. Boxes can be built with wood framing and insulated with everything from straw to discarded bubble wrap or even plastic drink bottles, though this does not produce the best insulation qualities. Cooling can be improved by using window air conditioners whose thermostats are bypassed by an external thermostat. Unlike the commercial refrigerators, these improvised facilities seldom meet modern hygiene standards, and the air conditioners typically take more water out of the air than is desirable for many vegetable crops, but that generally means that with the exception of onions or other crops that require dry air, they can't be used for long-term storage in the same way ascommercial refrigeration systems. It is possible to return some of the collected condensate from a window air conditioner to a room into a tray with wicking material to return much of it to the air inside the refrigerator to reduce the effect, but the boxes that are improvised construction are most often not airtight enough to allow the same level of control as a commercial cooling system charged specifically for maintaining a humidity range. Nor do improvised boxes often have doors with proper seals. They will not normally have the high-grade strip curtains behind the door that can reduce the cold air spilled out during a door opening by as much as 80 percent.

Case Study: Cooling-as-a-service (CaaS)

An advantage to the shared unit approach is that it enables cooling-as-a-service (CaaS) financial models to be employed. CaaS is an innovative business model for getting around financial barriers to expanding cold storage. CaaS is based on the idea that subsistence farmers and open-market vendors who cannot afford to purchase refrigeration equipment will be able to afford day-by-day pay-as-you-go refrigerated space rental when adding to the life of products they have on hand at that time. In other words, it makes refrigeration a product life-cycle cost rather than a long-term investment with ongoing overheads during potentially non-productive times. The basic mechanism is that investors set up refrigerated facilities with numbered internal bins that are rented by the day through a cell phone PayGo app. This is generally established near open-air markets at present, but a version of it for very small farms is also practical. Currently, there is a CaaS app developed by the BASE SET Alliance called the Cold Chain Virtual Assistant,[44] which allows a renter to track the age and condition of their stored product to prioritize handling and selling. It also handles PayGo transactions and gathers data for central databank information on the use and quantities of products. An additional objective here is to create small businesses that employ attendants and that pay loan or leasing costs for the refrigerated facility wherever outright ownership of refrigeration equipment is not economically practical for a farmer or fish producer. CaaS is typically more effective where demand for cooling is aggregated, such as in the operation of a walk-in cold room that is used by multiple agricultural producers.

[44] https://set-alliance.org/

Cooling Equipment for Fish

Fish spoil quickly. A fishing vessel that is out on the water for a number of hours each day will have its earliest catch already starting to deteriorate by the time it returns to shore. For this reason, the best approach to keeping fish fresh is to chill it on the shipping vessel as soon as it is caught. Commercial fishing vessels often have large-hold refrigerators. Very large ones, especially those that sail far from their home ports, often have complete fish processing facilities on board and hold freezers so they have market-ready products when they return to land.

Unfortunately, these solutions are not practical for smaller fishing boats, which are also the ones that suffer the highest losses. Instead, the most practical solution is to provide an insulted box that is filled with ice that was made on shore. This can be done with ice blocks, but the easiest form is shaved ice that can be loaded into the box with a shovel without having to be broken up first, and used to line fish bins or trays that fresh fish are transferred to for refrigerated storage or to carry straight to a local market. For the above reasons, ice making and refrigerated storage are both needed to maximize the shelf life for fresh fish. When fish come into dock already chilled on ice, it is cold enough that refrigeration equipment is not taxed with cooling it, and thus can be made for minimum power demand. The exception would be freezers when they are used to provide long-term storage.

There is a wide range of ice-making equipment. Block ice can be made in simple chest-style home freezers, but the rate of production is slow, and the finished product is harder to use than shaved ice. Shaved ice equipment is made in different scales. Smaller units that produce up to half a ton of ice a day will usually have the ice maker and shaver and a storage bin combined in a single unit. Larger units have freezing and shaving equipment separate from the storage box. This allows a user to construct a separate insulated box akin to a refrigerator box and to mount the freezing and shaving equipment on the roof of the box and let the ice fall through chutes into the box. People use the ice by opening the door and shovelling ice out into buckets or wheelbarrows or whatever they need to get it to their insulated boat boxes. Examples of ice-making equipment typically found in Sub-Saharan Africa are shown in the pictures below.

Figure 42. Example of a 300 kg ice maker

Figure 43. Example of a roof-mounted ice maker for an ice room

Figure 44. Example of an ice room as seen from the entryway

The downside to making ice is that it is an energy-intensive process. In addition to the removal of heat from water to freeze it, heaters are needed to release the ice from its forms, and a substantial electric motor must be run to perform shaving. Also, ice making requires a source of high-quality water, and it has maintenance requirements such as periodic descaling of water mineral deposits. A commercial shaved ice maker will consume a little over 5 kW to make a ton of shaved ice per day.

The refrigeration equipment needed to store fresh fish is like the crop refrigeration equipment already described, with the addition that it needs to be able to operate in the range of -1°C to 0°C. A freezer version is needed if the fish is to be frozen. Some countries require fish to be frozen to -40°C to kill parasites before they will allow it to be imported. Flash freezing equipment is also used in order to maintain the best flesh texture of the fish and so that, when it is thawed, it maintains most of the qualities of fresh fish. Examples of refrigeration equipment needed to store fresh fish are presented in the figures below.

Figure 45. Example of a fish blast freezer

Figure 46. Example of fish cooled on racks in a freezer

Figure 47. Example of high-volume freezer refrigeration equipment

Fresh Milk Harvesting Equipment

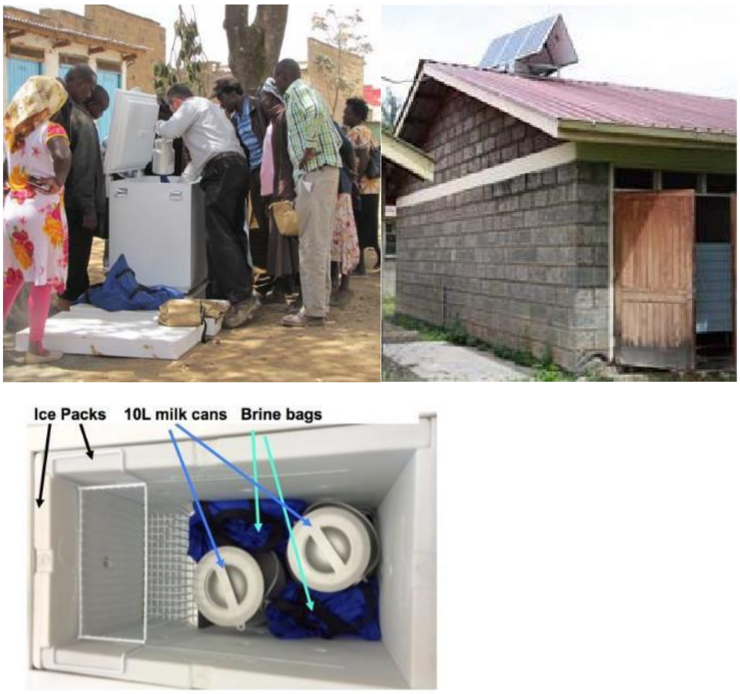
Fresh milk requires chilling as quickly as possible after harvest to minimize bacterial growth. It should ideally be chilled in half an hour, but four hours to reduce it from the harvest temperature to 8°C is a minimum cooling rate and it is further reduced to 4°C afterward. For a typical commercial milk collection operation, stations are established within reach of farmers who bring milk to the stations in cans and are generally then paid for it on the spot. Before it is accepted, a methylene blue test is normally performed to test for bacterial contamination, and when it passes, it is added to a large stainless steel tank with an inner liner of perhaps a couple of thousand liters capacity, that contains a stirring mechanism and has refrigeration tubing bonded to its outside, and then an outer tub so the air space between the tubs provides some insulation. The tank also has pumps to later move the chilled milk to a refrigerated collection truck.

In addition to these devices, alternative technologies and processes do exist. For example, smaller capacity systems that work by freezing a phase change material (PCM) with direct solar drive cooling systems during the day and then use that "stored cold" to chill milk very rapidly. The smallest kind of device like this is Sundanzer's[45] solar milk chiller system developed under the PV-

[45] See https://pdf.usaid.gov/pdf_docs/PA00Z5R4.pdf for more information.

Smart initiative (see Figure 48). This uses a chest-style PCM refrigerator to freeze PCM and can chill up to 40 liters of milk after a day of PCM freezing. This system is designed to be installed directly on a farm.

Figure 48. Sundanzer farm milk chiller (Source: USAID, 2018)



Larger versions for 200 to 500 liters per day are made by Promethean in India and by John Spears in the US. These add pump capacity for collection trucks. Examples of both are shown in the figures below.

Figure 49. Example of a Promethean system

Figure 50. Example of a commercial collection point chiller

Analysis Approach

For the cold chain overview, the following general assumptions were taken:

- Initial cooling will be at farms, ranches and fisheries where initial aggregation of crops will occur close to their point of production.
- Means of cold transport from the aggregation sites to larger sites or to processing facilities must be provided and are subject to seasonal disruption.
- Larger sites at community centres will be built to receive the production that is not being taken to commercial processing facilities. These will be distributed to local markets and may provide cooling-as-a-service (CaaS) to local market stall operators to offset costs.
- Means of cold transport will also be used to move excess stocks to larger urban warehouses when that is not done directly.

For each value chain, the agricultural cold chain team performed a multi-step data collection and analysis process.

First, during a two-week field mission in Madagascar, various stakeholders were interviewed along each value chain. These stakeholders included farmers/fishermen, exporters, importers, processors, agri-food public and private services, government ministries (of agriculture, livestock and fisheries), NGOs, hotels, restaurants, airports and handling services companies.

Secondly, the cold chain systems and technologies in use were mapped for each value chain in target areas as they exist. These systems were then observed to gauge the use of the technologies to assess if they met cold storage requirements to ensure food quality and safety.

While interviewing key stakeholders, the consortium team was able to identify gaps in cold chain requirements that contribute to post-harvest loss. From these interviews and observations an evaluation of cold chain system requirements was undertaken, which included temperature control, food safety and quality practices, and management of food in cold rooms. The team evaluated the costs of cold room construction, refrigeration services, electricity, customs services and other budgetary considerations. Moreover, an assessment of the number of cold containers that are used for export/import of food via multiple transportation methods was undertaken to determine the adequacy of the country's existing cold storage infrastructure to meet future targets.

From the field analysis, it is apparent that there are post-harvest losses at each step of value chains (from farm to retail, processing and distribution) due to existing equipment, equipment deficiencies, energy supplies and distribution and their deficiencies. This in turn allowed for the determination that additional energy supplies and types are needed to power equipment required to maintain the value chains. A projection of the capital expenditure (CAPEX) needed to acquire additional cold chain equipment and energy sources was developed.

Energy Forecasting Methodology

For the crops examined, the total annual production was determined from published data and the harvest period. This reveals how many tons are harvested and how quickly. It also determines the expected worst-case field temperature of the harvest. The crop or product is then characterized by its simple specific heat and, in the case of fresh horticultural products, their heats of respiration. This information is taken from USDA Handbook #66 and industry sources and is used to determine the product's contribution to the heat load on the refrigeration system both during cooling and in holding the cooled product.

Next, the refrigerated box heat load is determined. Standard practice for designing food refrigeration equipment is available from the ASHRAE handbook[46] and from the United States Department of Agriculture (USDA). Several refrigeration industry best practices are involved in the process. One is that with walk-in refrigeration equipment, half the space is occupied by product(s), and half is in aisles and airflow space. This is used to determine the required box volume. Another best practice from ASHRAE and cited in USDA Handbook #66 is that design will generally require 10–14 kW of cooling per 1,000 m^3 of space. This range was used as a cross check to compare the calculated load numbers to confirm harmonization in the more detailed method results.

Following this step, the above information was combined to determine the total heat load. An assumption was made that loads must be cooled in time frames suggested by the USDA documents specific to the harvest examined.[47] Door openings assume a strip curtain and opening the door only a couple of times a day for crop placement and retrieval. This number goes up dramatically in CaaS and market refrigerator situations and becomes a major load factor that isn't present for crop cooling and holding.

Then, refrigeration capacity is determined by the number of watts of cooling capacity needed to meet the calculated load and adds a safety margin of 20 percent to the result. Power consumption is then based on a sliding scale of likely cooling system overall coefficients of performance, which are smaller when the refrigeration unit is smaller and vary from 1.5 for units in the five-ton capacity range to 2.7 for large warehouses. Some modern systems can do better, but investment in those technologies cannot be assumed now.

For fish, ice is used to achieve initial cooling on board the fishing vessels. Ice making is more energy intensive than refrigeration, as the icemakers need not only to freeze water, which requires a bigger ΔT in the cooling system, but also have to run heaters to free the ice from the forms and then motors to shave the ice into flakes. Most units consume approximately 5 kW of constant electrical power (24hrs for seven days a week) to produce one metric ton of shaved ice per 24-hour period. Once chilled by ice, the fish is generally placed on trays with more ice and then the trays are placed in a refrigerator set to hold temperature at -1°C. This produces a light load for the refrigerator if the ice is present. The ice/fish trays must be designed to prevent melting ice water from trays from falling on trays below them to prevent bacterial contamination if a bad fish gets into the mix. The assumption used for ice making is twice as much ice as is needed to chill the fish must be made to have remaining ice for trays or for iced transport off the boat ice boxes.

[46] See - https://www.ashrae.org

[47] The time frames suggested by USDA are applicable based on the potential stability of the product and regardless of geography, hence they were applied in this study.

For potatoes, to maximize shelf-life, they first need to be cured for several weeks at 15°C and 90 percent relative humidity (RH). This is a compromise temperature that is lower than the fastest curing, which occurs at about 20°C and 90 percent RH. But the longer cure time associated with 15°C is considered worthwhile as it minimizes the chance of decay during curing. Once cured, potatoes are kept at 95– 99 percent RH to avoid shrinkage. The storage temperature depends on the end use. For fresh consumption, 7–10°C is used. For maximum life (up to a year), 3°C may be used. For seed potatoes, 4–5°C is used as sprouting increases just above 4°C. Ultimately, potatoes don't require refrigeration and in many parts of the world they are excluded from cold chain investment. Nevertheless, to maximize shelf life and minimize spoilage, a considerable amount of refrigeration and humidity control is required. Energy efficiency improvements are possible if the potato harvest can be segmented by long- and short-term storage, to save on refrigeration costs.

For tomatoes, the correct storage temperature varies depending on their maturity/colour. Generally, the riper the tomato, the colder its storage temperature. Tomatoes stored at temperatures that are too cold for their ripening stage will suffer chilling injury, reduced taste and quality and may never fully ripen. On the other hand, tomatoes stored at temperatures too high for their ripeness stage may be prone to spoilage, rot and premature damage. Ripe green tomatoes can be stored between 14°C and 16°C, while pink tomatoes can be stored between 9°C and 10°C. Fully ripe tomatoes can be stored at temperatures as low as 4°F. The correct humidity level for storing and cooling tomatoes is approximately 85 percent to 95 percent, with lower humidity levels risking drying out or dehydrating tomatoes and higher humidity levels making tomatoes more susceptible to rapid decay. Some studies suggest an even narrower range, around 85 percent to 90 percent, amid concerns that even humidity levels above 90 percent can accelerate degradation (Source: https://semcoice.com/methods-cooling-tomatoes-harvest/).

Dairy must be cooled from 37°C to 4°C as quickly as possible, ideally within 30 minutes of completion of milking, to minimize the increase in total bacterial count. It must then be kept at 4°C (Source: https://www.plevnik.eu/importanceof-milk-cooling/).

The electric demand per cooling watt for various standard refrigeration sizes used in the analysis is presented in Table 24. See Annex 3 for further details on the refrigeration load and sizing requirements methodology.

Table 24. Electric demand per cooling watt assumptions

Standard Refrigeration (above freezing)	Net System C.O.P.	Watts Electric Demand per Cooling Watt
10-30 m³	1.5	0,667 W/W
30-100 m³	2.4	0,417 W/W
100 m³ and larger	3	0,333 W/W

Refrigerated transportation is sized based on the distance between locations of the facilities that accumulate and distribute food. The portion kept by the farmer for personal use or taken to a local farmers' market rather than transported to larger facilities is subtracted from the total for transport. The agricultural cold chain model used a parametric approach to calculate the cold chain requirements and costs at each stage in the value chain for each product. These values were used to analyze the total energy requirements per scenario as presented below.

For the purposes of analysis, the total annual crop quantities, measured in tons per year, were estimated as follows: 251,258 tons for potatoes, 40,864 tons for tomatoes, 124,538 tons for fish and 103,090 tons for dairy products. A portion of these crops is self-consumed: 10 percent of potatoes, 10 percent of tomatoes, 10 percent ofof fish and 3.8 percentof dairy products. For the purpose of a cold chain analysis, the total annual crop quantities that are analyzed for cold chain requirements are then 226,132 tons for potatoes, 36,777 tons for tomatoes, 112,084 tons for fish and 99,121 tons for dairy products.

The analysis approach then assumes aggregation of crops at various levels of the supply chain. At the farm level, 90 percent of potatoes, tomatoes and fish are aggregated initially, while 96.15 percent of dairy products are aggregated. At the farm level, sub-portions of crops are designated for transport. For local markets, 81 percent of potatoes, 100 percent of tomatoes, 90 percent of fish and 72.1 percent of dairy products are allocated. From that, sub-portions for transport to regional or urban centres include 60 percent of potatoes, 60 percent of tomatoes, 50 percent of fish and 24 percent of dairy products.

Once the products leave the farms, further aggregation of crops takes place at regional and urban centralized levels. At the regional level, 30 percent of potatoes, 50 percent of tomatoes, 90 percent of fish and 14 percent of dairy products are aggregated with other crops. At the urban centralized level, 40 percent of potatoes, 30 percent of tomatoes, 30 percent of fish and 16.8 percent of dairy products are similarly aggregated. Finally, portions of these crops are designated for delivery to retail storage (30 percent of potatoes, 30 percent of tomatoes, 20 percent of fish and 6.8 percent of dairy products) or for processing (10 percent of potatoes, 10 percent of tomatoes, 15 percent of fish and 7.9 percent of dairy products). These parameters were used to define the distribution product within the supply chain.

Table 25. Parameters used to analyze cold chain requirements within each value chain.
(Source: Mission observations June 2023 and MAEP 2022)

Parameter	Unit	Potato	Tomato	Fish	Dairy
I. Total Annual Crop Quantity	tons/year	251,258	40,864	124,538	103,090
Portion of I. that is consumed by the farmer:	%	10%	10%	10%	3.8%
Remaining portion of I. for Cold Chain Analysis:	tons/year	226,132	36,777	112,084	99,121
II. Portion of I. Initially aggregated at Farm Level:	%	90%	90%	90%	96.2%
III_1. Sub-portion of II. for transport to local markets:	%	81%	81%	90%	96.1%
IV_1. Sub-portion of III_1 for refrigerated storage or transport:	%	9.0%	9.0%	9%	72.1%
IV_2. Sub-portion of III_1 for local processing:	%	10%	10%	60%	96.1%
V_1. Sub-portion of IV_1 for transport to Regional Centre:	%	60%	60.0%	50%	72.1%
VI_3. Portion of V_1 to be aggregated with other crops and delivered to Retail Stores:	%	60%	60.0%	50%	72.1%
V_2. Sub-portion of IV_1 for transport to Urban Centre.	%	40%	30%	50%	16.8%

VI_1. Sub-portion of V_2 to be frozen:	%	0.0%	0.0%	11.1%	24.0%
VI_2. Sub-sub-portion of V_2 to be aggregated with other crops:	%	50%	50%	63.0%	37.0%
VI_3. Portion of V_2 to be delivered to Retail Stores:	%	40%	40%	14.8%	18.0%
VI_4. Sub-portion of V_2 to be delivered for processing:	%	10%	10%	11.1%	21.0%

Estimation of transportation requirements

The number of tons of product used at each location when it is shipping is multiplied by the kilometers it must be moved. Distances were derived from the field study to determine average values for kilometers from farm to market, etc.[48] This is divided by the period of travel for that number of tons to arrive at a unit of ton-kilometers/period (day, year), with t-km/day being the common unit during the harvest period of the crop. This determines how much total cold transport is needed for the products analyzed in those units. Additionally, the estimated annual travel range limit of 50 km/day is assumed due to the very rough rural road conditions. So, for example, a five-ton refrigerated truck traveling 50 km with payload in one day has a transport capacity of 5 t × 50 km/day, so it can provide 250 t-km/day toward satisfying the transport requirement. It should be noted that exact numbers are in flux as roads and new cold storage facilities are built. Additionally, fuel cost assumptions improve with road conditions as less energy is spent on the cooling itself, particularly if a driver is having to idle his truck all night because a trip from farm or regional storage to an urban warehouse cannot be made in a day.

Cost Assumptions

Costs for refrigeration equipment are determined on a per-cubic meter basis, except for ice making, which is determined on a ton-produced basis. The value is determined by comparing costs for developed country equipment to costs for equipment purchased from India, for which about 2.5:1 is typical. Developed country costs are on the order of USD 3300/m² of floor space in warehousing that has height about half the length and width dimensions. From India, this is assumed to be about USD 1,300. For smaller walk-in coolers of 20 m³, delivered costs are in the USD 15,000 range. The designs are evaluated based on these values.

For transportation, Chinese-made refrigerated trucks were priced in capacities of five and ten tons. Poor road conditions in Madagascar in rural farming areas make the feasibility of large tractor-trailer-size vehicles doubtful (see the section above on accessibility for more information). The estimated mileage and maintenance costs were applied to the assumed range limitation of 50 km/day of travel outlined under assumptions, and this, combined with the annual amounts of crop produced for shipment, allowed an estimate of the number of vehicles needed to achieve the total

[48] Based on the field study, average distance from farm to regional markets was set at 30 km, regional markets to urban markets at 200 km, and urban aggregation centers to retail location at 20 km. More details on the cost basis for transportation estimates are provided in the Annex.

number of ton-kilometers per day of transport for food. A summary of key cost assumptions is presented in Table 26.

Table 26. Agricultural and fisheries cold chain cost assumptions

Cost Assumptions	Value (USD)	Unit
Average Ex-factory Refrigerated Truck Cost China	$3,000	USD per ton
Truck Operations, Maintenance and Fuel allowance	$1,600	USD per Year per Ton
Chipped Ice making @ 2t/day	$7,550	USD
Ice Maker Insulated Box and Steel Reinforcement.	$9,000	USD
Average cost to customer per kW installed mini-grid:	$2.66	USD/kWp
Average cost to customer per kW individual solar install:	$3.25	USD/kWp
Average cost to customer for grid kWh:	$0.13	USD/kWh

Methodology for Energy Consumption and Infrastructure Investment

Due to the nature of the analysis undertaken in the Integrated Energy Plan (IEP), the model develops a comprehensive overview of existing agricultural cold chain infrastructure while also suggesting areas for improvement across key value chains. While a detailed microeconomic or energy consumption survey of every farm, ranch and fishery and their production was infeasible, cross-cutting themes and insights could be developed that benefit the agricultural sector. These themes were derived from analysis of potato, tomato, dairy and fish value chains.

The analysis was focused on cold chain systems based on existing national annual production data by value chain from which total energy requirements can be extrapolated. For horticultural products, the varying harvest periods mean that the same cooling and storage equipment used by the representative crops can be used for other crops with different harvest periods. This cold chain complementarity is subject to accommodating temperature setting adjustments in the cold chain equipment (CCE) for corresponding horticultural crops. Fish and dairy needs are less variable than horticultural cooling requirements, so the latter was narrowed to two crops to serve as examples, namely potato and tomato, which have divergent harvest seasons and temperature requirements.

During the two-week field mission to study Madagascar's existing cold chain capabilities, the vast diversity of Malagasy farming practices and infrastructure accessibility became apparent. To present cost analysis, CCE recommendations would have to be made based on discrete facility sizes that represented average needs. Thus, in addition to a fixed selection of crops, a fixed set of facility sizes was developed based upon global best practices to address needs at different stages of cold chain implementation. Although actual cold chain development involves a multiplicity of sizing flexibility and customization based on local requirements, an approximate order of magnitude for cold chain investment can be derived from uniformly sizing infrastructure to accommodate total annual throughput corresponding to national production quantities. While the individual facility sizes will not correspond to fixed locations within the geospatial model, the cumulative quantities of energy consumption will approximately correlate to national cold chain requirements and the need for cold transport between facilities.

Thus, the four value chains under consideration (potato, tomato, dairy and fish) were each dimensioned according to national yield to develop commensurate CCE for infrastructure at the following scales: local farm, regional distribution centre, urban stockpile and retail market facility. Each facility size was assigned a corresponding energy consumption characteristic and the necessary solar standalone system sizes and associated costs.

The energy demand and estimated system costs will vary according to each agricultural value chain. These estimates include initial cooling capacity requirements for each crop per metric ton at the farm level and the cooling capacity required to maintain the products at a safe storage temperature. For these purposes, cost estimates are based on indicative product-specific data such as simple specific heat, the heat of respiration where applicable and the likely temperature at which the product will enter a chilling or refrigeration unit. There are also baseline assumptions about heat gained through the typical refrigeration box's insulation and for heat gain due to opening and closing the door to load and unload the cooling unit.

Based on the methodology defined previously, each of the four agricultural products were considered to be produced, transported, stored and sold in uniformly sized building blocks which, taken collectively, form an integrated national cold chain. Specifically, the facility characteristics were derived as shown in Table 26. But note that the farm allowance can either be for a single or a shared facility for which the listed kWp is the individual farm's share and is not the actual array size. For example, an average tomato farm will produce 51 kg/day during harvest, which requires about 1.74 kWh/day to cool, which 0.4 kWp of solar modules can supply. However, 10 such farmers may share a common unit large enough to cool their combined payloads, and such a unit would have a single 4 kWp array to keep it running.

Based on field observations, the percentage of farm output sent to regional facilities was divided among 20 facilities, of which we would expect more than one in the high-producing regions and none in low-producing regions where output all goes to local farmers' markets. The solar sizing is for each of these facilities operating to store the product that arrives pre-chilled by the farm facilities. The portion sent to urban centres was divided among three large warehouse-size facilities for each product. In practice, it may be there will be a larger number of smaller warehouses, but because we are using the energy needed by each value chain among these facilities, the total kWp allowance should remain correct.

One exception would be combined use. For example, because potatoes and tomatoes are harvested at different times of year, the same facility that cures and stores potatoes can be used to chill and store tomatoes. If all tomatoes were produced on farms that also produced potatoes, the larger of the two energy requirements (potatoes) would be all that was needed, and the energy requirements of tomatoes could be dropped to zero. From field observations, there is about a 70 percent overlap, so the requirements for tomatoes could be dropped to 0.12 if that sharing scheme is used, and tomatoes would be a bonus. Unfortunately, we did not have the data granularity to do more than the rough estimate, so tomato demand was given its full measure, as that also rather neatly produces an allowance for older or less efficient refrigeration equipment to be adapted to both potatoes and tomatoes with the combined kWp of both.

Table 27. Simulated cold chain infrastructure dimensions

Facility	PV Size – Potato (kWp)	PV Size – Tomato (kWp)	PV Size – Fish (kWp)	PV Size – Dairy (kWp)
Local Per-Farm Install Allowance	2.5	0.4	0.6	5.4
Regional Storage	137	13	15	5.5
Urban Storage	363	54	23	10
Retail Market	0.2	0.0	0.1	0.0

Once the system dimensions were established for each facility size and value chain, cost estimates were performed based on high-level quotations from suppliers in the Sub-Saharan African solar market. These cost assumptions are slightly higher than those presented in the electrification report, considering these solar arrays will be at a facility scale rather than a community scale with primarily rooftop or small ground-mounted systems. These systems are often very specific to their facility's context and may not achieve as beneficial economies of scale as larger, community-based systems.

Scenario Development for Agriculture and Fisheries Cold Chain Analysis

The agricultural cold chain analysis is a new aspect of the Madagascar Integrated Energy Plan (IEP) that has not been considered in prior IEPs. Two scenarios were evaluated within the agricultural cold chain analysis:

Scenario 1 - 100 percent development of cold chain in all four value chains. This scenario represents a totally developed cold chain investment for the four value chains.

Scenario 2 - 20 percent development of cold chain in all four value chains. This is a reasonable objective for a decade-long target for improvement of cold chain function. This level of improvement serves needs as well as setting an example for businesses to see what cold chain development can do for them.

Before presenting the summary of results, the section below shows details per-value chain on the cold chain requirements, costs and insights.

Analysis by value chain

Potato

As mentioned in the overview, potatoes are produced primarily in the Anamalanga, Itasy and Matsiatra Ambony regions. The ideal harvest consists of washing potatoes followed by curing them for two weeks at 15°C, in 80 percent–100 percent relative humidity (RH) conditions. This curing stimulates suberization and wound healing and reduces respiration, and doing it at 15°C minimizes decay, and is necessary for long-term storage.[49] To produce these conditions, refrigeration is designed to cool potatoes to 15°C and the evaporator and condensing system is designed to maintain humidity in the above range. The assessment of required cooling capacity is based on potato simple specific heat capacity of 3.43 MJ/t-K and average heat of respiration of 10 MJ/t/day.[50] The cooling rate target is one day to reach 15°C by sizing the cooling system to be able to pump the required heat out in about eight hours, understanding actual heat transfer will be limited by how potatoes are boxed and will take roughly three times that long to settle. Calculations arebased on potato bulk density of 0.728 t/m^3[51]. Based on these parameters, the cold chain requirements (energy and cold transport needs) from the farm to regional warehouse to urban retail centre are presented in Table 28.

Table 28. Cold chain analysis of potatoes

Potatoes	Values	Units
Total Annual Crop Quantity	251,258	Tons/Year
Total Annual Crop Quantity minus self-consumed quantities	226,132	Tons/Year
Farm Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	3,899	Tons/Day
Required Energy at Farm	4.57	kWh/day
Projected Nationwide Energy Demand in this Category:	58,790	kWh/day
Cold Transportation Capacity Needed to Local Market:	No Cold Transport Needed	
Regional Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	3,158	81% of total annual crop Tons/Day
Required Energy at Regional Warehouse	1,641	kWh/day
Projected Nationwide Energy Demand in this Category:	33,228	kWh/day
Cold Transportation Capacity Needed to Urban Cooler:	37,897	Tons·km/day
Urban Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	2,339	60% of total annual crop Tons/Day
Required Energy at Urban Warehouse	5,355	kWh/day
Projected Nationwide Energy Demand in this Category:	16,215	kWh/day

[49] Source: USDA handbook 66, p 507.
[50] Source: USDA handbook 66, p 508, and The Engineering ToolBox (2003). Food and Foodstuff - Specific Heat. [online] Available at: https://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html, 7/11/23.
[51] Source: Evaluation of physical and mechanical properties of fresh potato, MB Patel, ER Alok Nath and Dr. JM Mayani, International Journal of Chemical Studies 2018; 6(5): 1454-1459.

Cold Transportation Capacity Needed to Retail Cooler:	15,595	Tons·km/day
Retail Market Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	2,339	Tons/Day
Required Energy at Retail Market	3.38	kWh/day
Projected Nationwide Energy Demand in this Category:	35,830	kWh/day
National Totals		
Ideal Storage Nationwide Power Consumption Summary:	144,064	kWh/day
	52,583	MWh/year
Cold Transport Total:	53,504	Tons·km/day

Supposing that a totally developed cold chain is required, the results of the **Scenario 1** cold chain analysis for potatoes are presented in Table 29.

Table 29. Potato scenario 1 analysis by region.

Scenario 1 100% Crop Inclusion 100% Cold Chain Use by Region	Quantity Annual Crop Quantity in Cold Chain Analysis in Tons/Year	Refrigeration Energy Demand in MWh/Year	Cold Chain Transport in t-km/year	Capex Cost In USD
Alaotra-Mangoro	0	0	0	$0
Amoron'i Mania	0	0	0	$0
Analamanga	103,983	21,762	8,081,995	$103,651,906
Analanjirofo	0	0	0	$0
Androy	0	0	0	$0
Anosy	0	0	0	$0
Atsimo-Andrefana	1,756	368	136,506	$1,750,699
Atsimo-Atsinanana	0	0	0	$0
Atsinanana	12,897	2,699	1,002,413	$12,855,992
Betsiboka	0	0	0	$0
Boeny	3,754	786	291,760	$3,741,838
Bongolava	0	0	0	$0
Diana	0	0	0	$0
Fitovinany	0	0	0	$0
Ihorombe	0	0	0	$0
Itasy	80,654	16,879	6,268,745	$80,396,911
Matsiatra Ambony	48,214	10,090	3,747,382	$48,060,322

Scenario 1 100% Crop Inclusion 100% Cold Chain Use by Region	Quantity Annual Crop Quantity in Cold Chain Analysis in Tons/Year	Refrigeration Energy Demand in MWh/Year	Cold Chain Transport in t-km/year	Capex Cost In USD
Melaky	0	0	0	$0
Menabe	0	0	0	$0
Sava	0	0	0	$0
Sofia	0	0	0	$0
Vakinankaratra	0	0	0	$0
Vatovavy	0	0	0	$0
Total:	**251,258**	**52,583**	**19,528,802**	**$250,457,668**

The results of Table 29 are presented graphically in the figures below, showing the calculated quantity of harvested crop in cold chain, refrigeration energy requirements and costs. In addition, the calculated quantity in cold chain map shows the roads and cities to contextualize the quantitative estimated of cold chain requirements for the potato supply chain within the country.

Figure 51. Potato – quantity in cold chain, scenario 1, with major cities and roads.

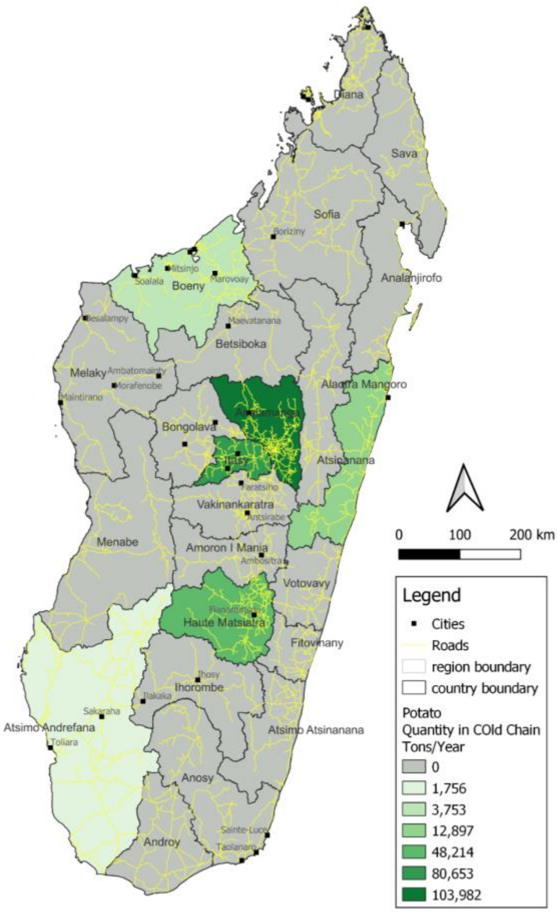


Figure 52. Potato – refrigeration energy requirement

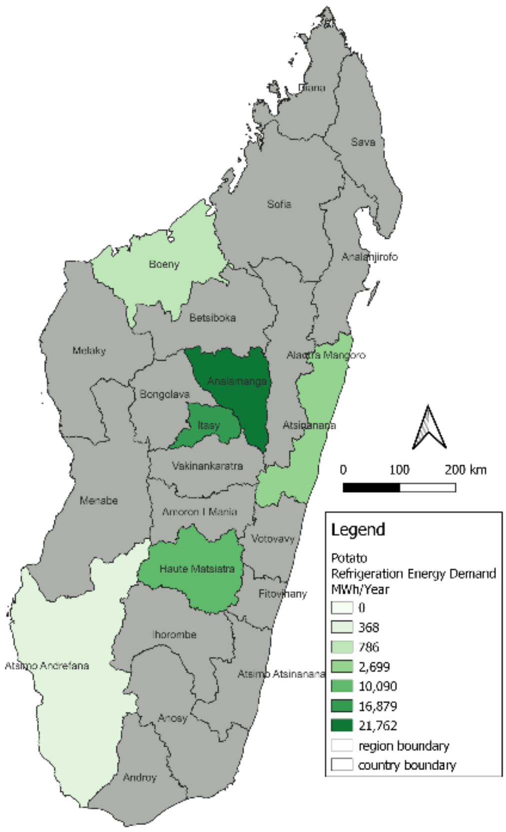
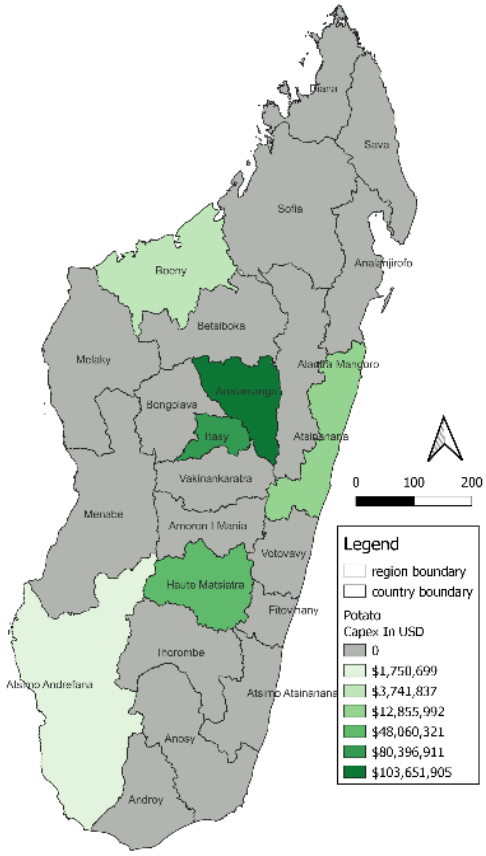


Figure 53. Potato – capex investments in USD



Based on the field mission, many small farms harvest an average of only a few kilograms of potatoes a day during the harvest months, and this is far too small to justify building separate cooling equipment, but most farms are in close enough proximity to share a single ripening facility. To make facility sizing practical, a facility that would accept about 0.3 tonnes per day would be shared by a farming community. This would mean a total of about 12,000 such facilities would need to be built, based on the annual harvest of 22,6132 t/yr (Source: MOA). Such a facility would accumulate and hold up to 4.2 t for a two-week ripening period. They would be removed for taking to market or for shipping at the rate of 0.3 t/day on a FIFO basis and replaced with the next day's harvest at that time. This would allow the use of commercial refrigeration with about 12 m³ interior volume. This is best practice, but it is expensive. The solar-powered units require a fair amount of solar just to maintain temperature with no load, so that even though the potato load is not particularly high, you use a fair amount of power in background cooling.

The costs can be mitigated by applying appropriate technology. For an individual farmer, a small root cellar may be perfectly adequate. Ground cooling will keep up with the few kilograms they harvest each day on average. However, if they try to harvest all in one day, temperature maintenance could become an issue, so training for rate of harvest is required for best practice in this regard. The cellar may also require lining with a vapor barrier material such as polyethylene sheeting to maintain adequate humidity during curing. The next step up would be a locally assembled cold room that employs a walk-in cold room with a window air-conditioning system in a wall, plus a solar system to operate that air conditioner. Here, the room should be insulated with extruded polystyrene foam or another insulation product and lined with a vapor barrier. Because air conditioners are designed to remove moisture, a modification that captures condensate from the unit and returns it to an evaporating surface in the room would be important to maintaining relative humidity.

Tomato

Tomatoes are produced primarily in the Anamalanga and Itasy regions and harvested throughout September and October. The ideal harvest consists of washing tomatoes and packaging them, followed by cooling to either 20°C for ripening, or to 13°C for storage, in 90 percent–100 percent RH conditions. Forced air cooling is preferred, as more passive cooling takes longer to overcome the heat of respiration when the tomatoes are packed. Tomatoes can be stored at 7°C for a couple of days, but they are vulnerable to chilling injury, and this compromises flavour.[52] To produce these conditions, refrigeration is designed to cool tomatoes to either 20°C or 13°C.The evaporator and condensing system are designed to maintain humidity in the above range and the evaporator fans are designed to remain on all the time to produce circulation during cooling. The assessment of required cooling capacity is based on an incoming field temperature of 32°C; tomato simple specific heat capacity of 3.97 MJ/t-K; and average heat of respiration of 24 MJ/t/day.[53] The cooling rate target is one day to reach 20°C by sizing the cooling system to be able to pump the required heat out in about eight hours, understanding actual heat transfer will be limited by how tomatoes are boxed and will take roughly three times that long to settle. Calculations are based on tomato bulk density of 0.481 t/m³. [54] Based on these parameters, the cold chain requirements (energy and cold transport needs) from the farm to regional warehouse to urban retail centre are presented in the Table 30.

Table 30. Cold chain analysis of tomatoes

Tomatoes	Values	Units
Total Annual Crop Quantity	40,864	Tons/Year
Total Annual Crop Quantity minus self-consumed quantities	36,777	Tons/Year
Farm Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	613	Tons/day
Required Energy at Farm	1.78	kWh/day
Projected Nationwide Energy Demand in this Category:	19,345	kWh/day
Cold Transportation Capacity Needed to Local Market:	2	Tons˙km/day
Regional Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	496	81% of total annual crop Tons/day
Required Energy at Regional Warehouse	253.5	kWh/day

[52] USDA handbook 66, p 582-583.
[53] Source: USDA handbook 66, p 584, and The Engineering ToolBox (2003). Food and Foodstuff - Specific Heat. [online] Available at: https://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html, 7/11/23.
[54] Source: table provided by Machine & Process Design, https://www.mpd-inc.com/bulk-density/

Projected Nationwide Energy Demand in this Category:	5,086	kWh/day
Cold Transportation Capacity Needed to Urban Cooler:	5,958	Tons*km/day
Urban Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	368	60% of total annual crop Tons/day
Required Energy at Urban Warehouse	1,031	kWh/day
Projected Nationwide Energy Demand in this Category:	3,123	kWh/day
Cold Transportation Cap Needed to Retail Cooler:	2,452	Tons*km/day
Retail Market Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	368	Tons/day
Required Energy at Retail Market	0.37	kWh/day
Projected Nationwide Energy Demand in this Category:	4,744	kWh/day
National Totals		
Ideal Storage Nationwide Power Consumption Summary:	32,298	kWh/day
	11,789	MWh/year
Cold Transport Total:	8,412	Tons*km/day

The results of the Scenario 1 cold chain analysis for potatoes, supposing that a totally developed cold chain is required, are presented in Table 31.

Table 30. Tomato scenario 1 analysis by region

Scenario 1 100% Crop Inclusion 100% Cold Chain Use by Region	QTY in Cold Chain in Tons/Year	Refrigeration Energy Demand in MWh/Year	Cold Chain Transport in t-km/year	Capex Cost In USD
Alaotra-Mangoro	0	0	0	$0
Amoron'i Mania	0	0	0	$0
Analamanga	3,211	926	241,240	$3,647,009
Analanjirofo	0	0	0	$0
Androy	0	0	0	$0
Anosy	0	0	0	$0
Atsimo-Andrefana	54	16	4,080	$61,679
Atsimo-Atsinanana	0	0	0	$0
Atsinanana	398	115	29,900	$452,021
Betsiboka	0	0	0	$0
Boeny	116	33	8,684	$131,289

Bongolava	0	0	0	$0
Diana	0	0	0	$0
Fitovinany	0	0	0	$0
Ihorombe	0	0	0	$0
Itasy	35,596	10,269	2,674,475	$40,432,127
Matsiatra Ambony	1,489	429	111,848	$1,690,895
Melaky	0	0	0	$0
Menabe	0	0	0	$0
Sava	0	0	0	$0
Sofia	0	0	0	$0
Vakinankaratra	0	0	0	$0
Vatovavy	0	0	0	$0
Total:	**40,864**	**11,789**	**3,070,227**	**$46,415,021**

The results in Table 31 are presented graphically in the figures below, showing the calculated quantity of harvested crop in cold chain, refrigeration energy requirements and costs.

Figure 54. Tomatoes – quantity in cold chain, scenario 1, with major cities and roads.

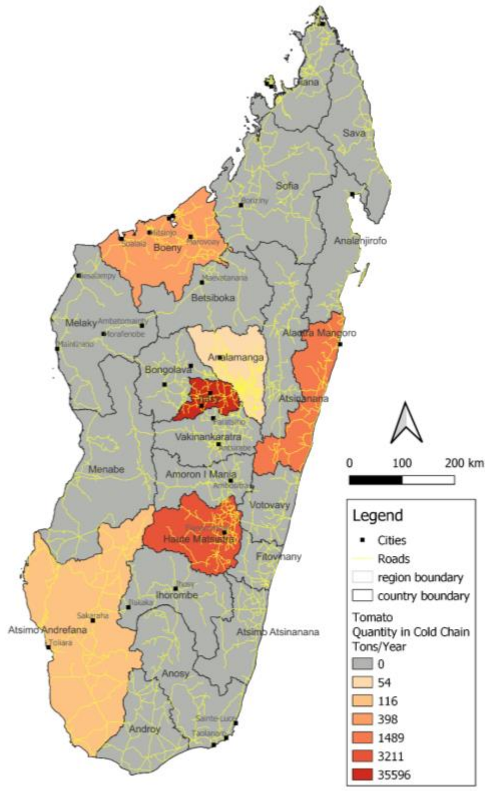


Figure 55. Tomatoes – refrigeration energy demand

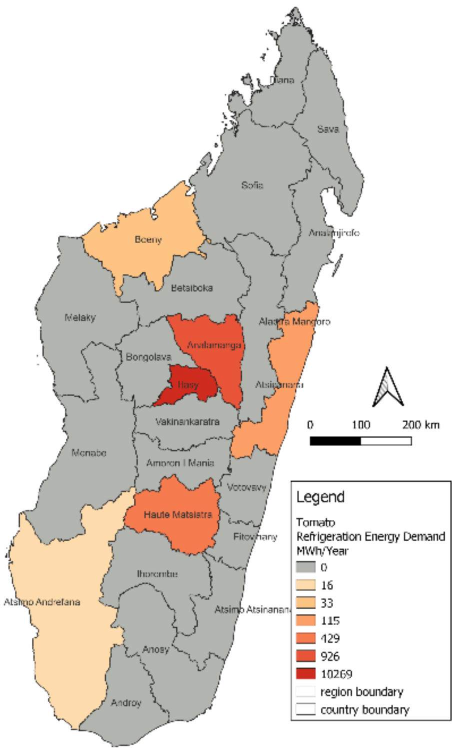
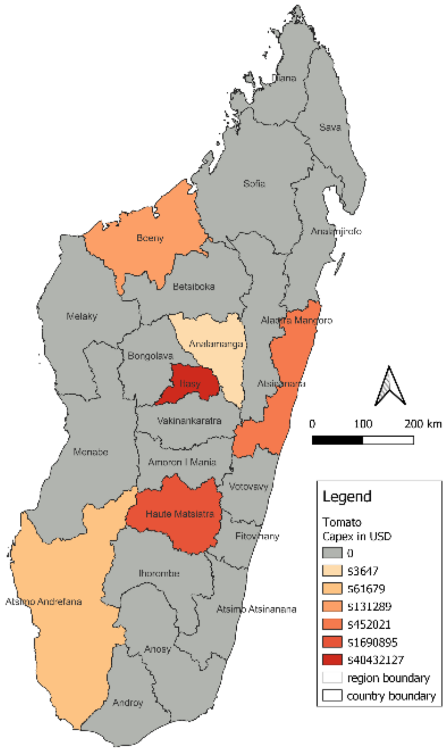


Figure 56. Tomatoes – capex investment in USD



Based on the field mission, many small farms harvest an average of only a few kilograms of tomatoes a day during the harvest months, and this is far too small to justify building separate cooling equipment, but most farms are in close enough proximity to share a single ripening facility. To make facility sizing practical, a facility that would accept about 0.1 tonnes per day would be shared by a farming community. This would mean a total of about 10,000 such facilities would need to be available, based on the annual harvest of 40,864 tonnes/year. Such a facility would accumulate and hold up to 1.5 t for a two-week ripening period. They would be removed for taking to market or for shipping at the rate of 0.1 t/day on a FIFO basis and replaced with the next day's harvest at that time. This would allow the use of commercial refrigeration with about 3 m^3 interior volume. This is best practice, but again it is expensive. The costs can be mitigated by using the same equipment that cures potatoes for tomato storage, and the two crops have two regions, Anamalanga and Itasy in common. Our field visit suggested about 70 percent of tomatoes could use cooling facilities already established for potatoes (see Potatoes section).

Fisheries

Fish are produced primarily in the Boeny, Diana and Atsimo-Andrefana regions. Fish are harvested throughout the year. Ideal harvest consists of having insulated boxes with ice on the boats, so fish are placed on ice as soon as they are caught and start chilling (the SmartFish concept). When the fish are caught, they are placed in bins or trays with ice and kept in a refrigerator and stored at a temperature range of -1°C to 0°C. The bins or trays need to be solid so that in the event of bacteria contaminated ice melt, the melt water cannot drip from one bin or tray to the next. For fresh fish, ice bins and trays are removed at the market as they are used on a rotating basis. Refrigerator evaporator and condensing systems are designed to maintain humidity in the 80 percent–100 percent range, so the fish and ice are not dried. The fact that fish arrives on ice minimizes payload cooling demand on the refrigerator, keeping smaller cooling capacities adequate. The assessment of required cooling capacity is based on needing enough ice to cool and hold fish that is caught in a worst-case water temperature of 30°C and fish simple specific heat capacity of 3.60 MJ/t-K.[55] Ice in ice boxes on the boats will accomplish most of the cooling and holding of temperature until the refrigerator is reached. Calculations are based on fish bulk density of 0.321 tonnes/meter^3.[56] Based on these parameters, the cold chain requirements (energy and cold transport needs) from the fishery to the regional warehouse to the urban retail centre are presented in Table 32.

Table 31. Cold chain analysis of fisheries

Fisheries	Values	Units
Total Annual Fish Quantity	130,724	Tons/Year
Total Annual Fish Quantity (minus self-consumed)	117,652	Tons/Year
Fishery Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	406	Tons/day
Required Energy at Landing	77.68	kWh/day
Projected Nationwide Energy Demand in this Category:	46,905	kWh/day
Cold Transportation Capacity Needed to Local Market:	24	Tons·m/day
Regional Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	365	90% of total harvest Tons/Day
Required Energy at Regional Warehouse	429.8	kWh/day
Projected Nationwide Energy Demand in this Category:	8,613	kWh/day
Cold Transportation Capacity Needed to Urban Cooler:	4,382	Tons·km/day
Urban Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	203	50% of total harvest Tons/Day
Required Energy at Urban Warehouse	4,605	kWh/day
Projected Nationwide Energy Demand in this Category:	13,845	kWh/day
Cold Transportation Cap Needed to Retail Cooler:	1,352	Tons·km/day
Retail Market Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	203	Tons/day
Required Energy at Retail Market	3.87	kWh/day
Projected Nationwide Energy Demand in this Category:	21,848	kWh/day
National Totals		
Ideal Storage Nationwide Power Consumption Summary:	91,212	kWh/day
	33,292	MWh/year
Cold Transport Total:	5,758	Tons·km/day

[55] The Engineering ToolBox (2003). Food and Foodstuff - Specific Heat. [online] Available at: https://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html, 7/11/23.

[56] https://www.fao.org/3/P3407E/P3407E07.htm#:~:text=The%20stowage%20density%20of%20bulked%20fish,is%20about%200.50%20t%2Fm%C3%AF%C2%BF%C2%BD%20of%20fishroom

The results of the Scenario 1 cold chain analysis for fisheries, supposing that a totally developed cold chain is required, are presented in Table 33. Note there is a 0.35 percent discrepancy in the regional distribution of annual fish yields as compared to the national total provided in Table 32.

Table 32. Fisheries scenario 1 analysis by region

Scenario 1 100% Crop Inclusion 100% Cold Chain Use by Region	QTY in Cold Chain in Tons/Year	Refrigeration Energy Demand in MWh/Year	Cold Chain Transport in t-km/year	Capex Cost In USD
Alaotra-Mangoro	510	130	719	$9,340,399
Amoron'I Mania	118	30	166	$2,155,477
Analamanga	157	40	221	$2,873,969
Analanjirofo	4,222	1,075	5,952	$77,357,663
Androy	65	17	92	$1,197,487
Anosy	9,425	2,400	13,285	$172,677,633
Atsimo-Andrefana	20,406	5,197	28,763	$373,855,457
Atsimo-Atsinanana	353	90	498	$6,466,430
Atsinanana	745	190	1,050	$13,651,352
Betsiboka	1,948	496	2,746	$35,685,114
Boeny	47,178	12,015	66,500	$864,346,153
Bongolava	0	0	0	$0
Diana	23,452	5,973	33,057	$429,658,354
Fitovinany	0	0	0	$0
Ihorombe	52	13	74	$957,990
Itasy	13	3	18	$239,497
Matsiatra Ambony	654	166	921	$11,974,871
Melaky	2,471	629	3,483	$45,265,011
Menabe	9,072	2,310	12,788	$166,211,203
Sava	4,654	1,185	6,560	$85,261,078
Sofia	1,647	419	2,322	$30,176,674
Vakinankaratra	444	113	626	$8,142,912
Vatovavy	2,680	682	3,777	$49,096,969
Totals:	130,267	33,176	183,617	$2,386,591,692

The results of Table 33 are presented graphically in the figures below, showing the calculated quantity of harvested crop in cold chain, refrigeration energy requirements and costs.

Figure 57. Fisheries – quantity in cold chain, scenario 1, with major cities and roads.

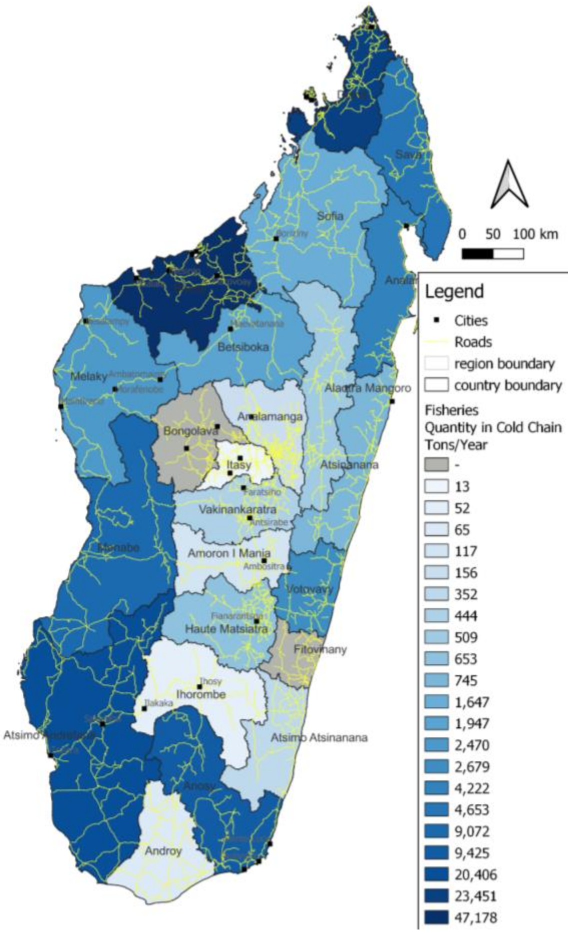


Figure 58. Fisheries – refrigeration energy demand

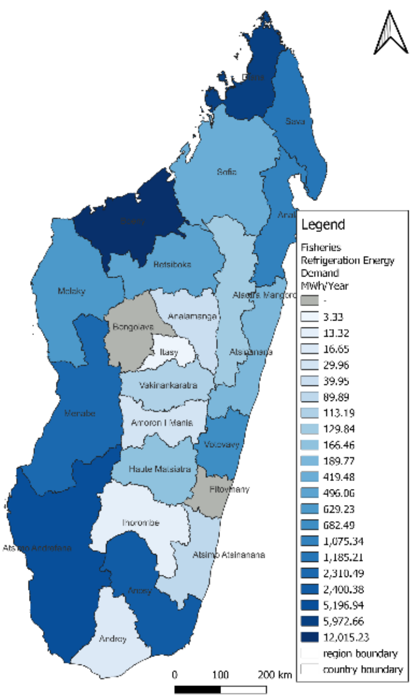
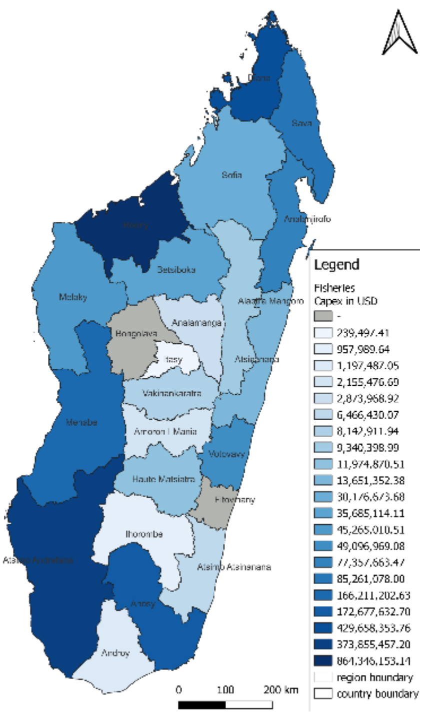


Figure 59. Fisheries – capex investment in USD



During the field mission it was noted that many small fishing operations have little or no ice-making or refrigeration capability, while large commercial facilities do. The assumption is therefore that investment should be focused on smaller fishing operations. This is reflected in combined harvest and post-harvest loss for smaller operations of as much as 85 percent when the amount of spoiled or partly spoiled fish that is consumed anyway is not counted. The potential to raise income by providing ice and refrigerated storage for aggregation at the fishery level is therefore correspondingly very high. However, ice making is somewhat energy and maintenance intensive as, in addition to powering the freezing units, heaters for ice release, motors for the shaver, and, in many places the need to provide water pumping and filtration to supply the machine must be considered. For these reasons power demand from ice making can range from 5–7 kW to produce one metric ton per day, for a total energy demand of 120–168 kWh/day.[57] Here, as with refrigeration equipment, it is most practical to provide a shared production facility at fishing boat docks or anchoring locations. Where these are located at the seaside, there is a further cost in commercial refrigeration to use stainless steel coils and piping to avoid corrosion by the salt spray in sea air.

In this evaluation, the pricing of ice equipment from China has proven most economical. Units producing approximately half a ton of shaved ice a day are in the USD 2,500 range and would make enough ice to allow a fishery to collect about 0.7 tonnes a day. This is expensive to establish because of the large solar power system required but return on investment (ROI) is quick because of the price fish commands. Refrigeration storage capacity is small because fish is generally turned

[57] Data derived from Holiday Ice Makers, Longwood, Florida, USA.

over in one day. Iced storage can extend that a day or two, but nothing will stay at the catch collection site for long.

In addition, there is some existing commercial equipment for fish already established. Refrigerators have been made both with electrical energy storage (batteries), and with phase change material (PCM) (thermal storage) that is frozen during daylight hours by solar electric power and then uses the PCM and circulating fans at night. Plus, commercial operations bring a good deal of their own equipment to bear, especially frozen fish for export. The fish sector overall has experienced some considerable assistance. Targeting the 20 percent of overall country cold chain capacity needs for fisheries is recommended, as other portions of the market are already gaining attention in Madagascar.

Diary

Dairy is produced primarily in the Vakinankaratra, Analamanga and Itasy regions. Milk is collected directly from cows. If it is to be sent to a processor or to be kept for any length of time, it must be chilled. By the time it is carried to a chiller, the average temperature is down to about 36°C. When it comes from the cow, milk has some natural anti-bacterial protection the cow provides to keep her calf safe from infection, but within four hours, this is gone. Additionally, there is concern for the sanitation of the milk-handling containers that could jumpstart bacterial growth by inoculating freshly collected milk. As a result, it is considered best policy to start chilling milk within 30 minutes of collection. A large circulating chiller may then take three hours or more to finish cooling it. However, the faster PCM-based chillers, like those made by John Spears (US) and Promethean (India), can chill milk rapidly to comply with best practice, which is to try to have it below 4°C within an hour.[58] The heat load from milk on the incoming temperature is 36°C and it has a simple sensible heat of 3.77 MJ/t-K. The density of milk varies by season but is about 1.03 t/m^3. Milk quantities are often expressed in liters, and there are 971 l/t.

[58] Raw Milk Institute: https://www.rawmilkinstitute.org/updates/rapid-chilling-of-raw-milk-lowers-pathogen-risks-and-improves-shelf-life

Table 33. Dairy cold chain analysis.

Dairy	Values	Units
Total Annual Crop Quantity	103,090	Tons/Year
Total Annual Crop Quantity minus self-consumed	99,121	Tons/Year
Farm Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	273	Tons/Day
Required Energy at Farm	25.1	kWh/day
Projected Nationwide Energy Demand in this Category:	305,537	kWh/day
Cold Transportation Capacity Needed to Local Market:	6.34	Tons·km/day
Regional Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	197	72% of total harvest Tons/Day
Required Energy at Regional Warehouse	178.6	kWh/day
Projected Nationwide Energy Demand in this Category:	3,572	kWh/day
Cold Transportation Capacity Needed to Urban Cooler:	2,363	Tons·km/day
Urban Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	66	24% of total harvest Tons/Day
Required Energy at Urban Warehouse	324.6	kWh/day
Projected Nationwide Energy Demand in this Category:	132	kWh/day
Cold Transportation Cap Needed from farms and Retail Coolers:	974	Tons·km/day
Retail Market Cooling and Cold Transport Need		
Harvesting and Initial Aggregation Rate:	66	Tons/Day
Required Energy at Retail Market	0.34	kWh/day
Projected Nationwide Energy Demand in this Category:	4,380	kWh/day
National Totals		
Ideal Storage Nationwide Power Consumption Summary:	246	kWh/day
	90	MWh/year
Cold Transport Total:	2,807	Tons·km/day

The results of the Scenario 1 cold chain analysis for dairy are presented in the table below.

Table 34. Dairy scenario 1 analysis by region.

Scenario 1 100% Crop Inclusion 100% Cold Chain Use by Region	QTY in Cold Chain in Tons/Year	Refrigeration Energy Demand in MWh/Year	Cold Chain Transport in t-km/year	Capex Cost In USD
Alaotra-Mangoro	979	1	9,733	$352,380
Amoron'i Mania	979	1	9,733	$352,380
Analamanga	28,391	25	282,159	$10,215,301
Analanjirofo	979	1	9,733	$352,380
Androy	979	1	9,733	$352,380
Anosy	979	1	9,733	$352,380
Atsimo-Andrefana	979	1	9,733	$352,380
Atsimo-Atsinanana	979	1	9,733	$352,380
Atsinanana	979	1	9,733	$352,380
Betsiboka	979	1	9,733	$352,380
Boeny	979	1	9,733	$352,380
Bongolava	979	1	9,733	$352,380
Diana	979	1	9,733	$352,380
Fitovinany	979	1	9,733	$352,380
Ihorombe	979	1	9,733	$352,380
Itasy	8,350	7	82,988	$3,004,500
Matsiatra Ambony	979	1	9,733	$352,380
Melaky	979	1	9,733	$352,380
Menabe	979	1	9,733	$352,380
Sava	979	1	9,733	$352,380
Sofia	979	1	9,733	$352,380
Vakinankaratra	46,762	41	464,732	$16,825,202
Vatovavy	979	1	9,733	$352,380
Totals:	103,090	90	1,024,541	$37,092,598

The results of Table 35 are presented graphically in the figures below, showing the calculated quantity of harvested crop in cold chain, refrigeration energy requirements and costs.

Figure 60. Dairy – quantity in cold chain, scenario 1, with major cities and roads

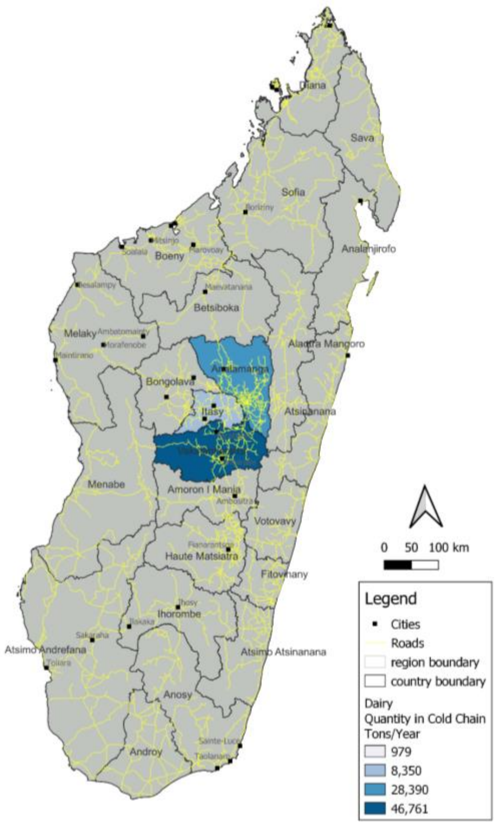


Figure 61. Dairy – refrigeration energy demand

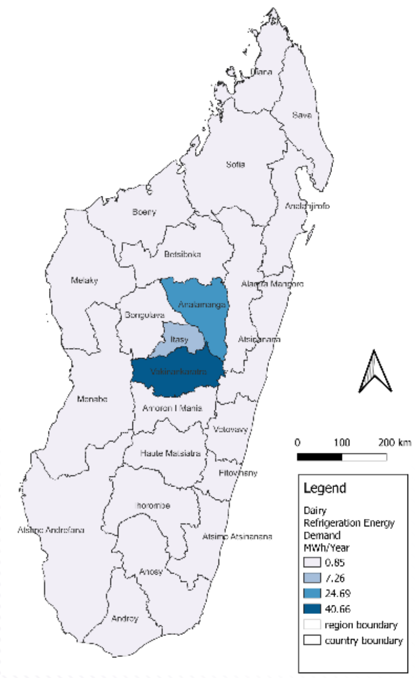
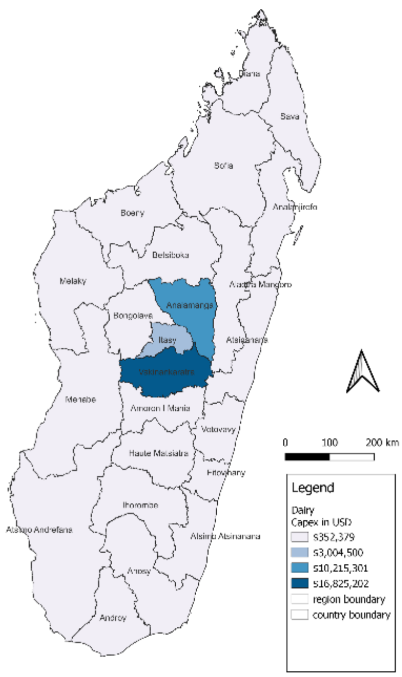


Figure 62. Dairy – investment capex in USD



The usual practice is to have a milk chiller with 500 to 2,000 liters capacity central to a community. At the collection site, a methylene blue test is done on a sample from each container brought to the site to check for bacterial content,[59] and if the milk passes, then it is chilled together with other milk brought to the collection point that has already been tested. After chilling, a refrigerated collection truck travels to the site to collect the milk. Currently, this is the procedure for between 6 percent and 10 percent of milk produced in Madagascar (sources disagree on exact amount), but there is the potential for much larger quantities if collection and cold chain transport equipment availability is expanded.

Consumption of milk by farmers is approximately 5 percent of production. Since refrigeration for milk is not widely available and keeping fresh milk in a hot market all day will spoil it, much of the rest is turned into homemade yoghurt or cheeses, as these processes involve heat rather than the unavailable cold. This makes it possible to take the finished product to an uncooled marketplace, where it lasts longer than fresh milk. Exact figures on milk spoilage and yoghurt loss and failures to process at the farm level are variable, but the harvest of fresh milk designated for processing can be significantly expanded as a cash crop for farmers.

Food Spoilage Analysis

There are three basic areas of crop loss:

- Pre-harvest losses
- Harvest losses
- Post-harvest losses

Pre-harvest losses encompass everything that prevents planted crops from reaching the level of maturity needed to provide a usable crop harvest. They include poorly stored or damaged starting seed stock, subsequent bad weather conditions, plant disease and pestilence that damages crops.

Harvest losses encompass anything that may damage a crop during the attempt to harvest it and make it suitable for consumption. In other words, anything that prevents finished production of the harvest. This can include mechanical damage due to the harvesting method, improper curing, bad sanitation practices, heat damage, damage by vermin or pests, or other handling errors that result in the produce never becoming suitable for sale or consumption. Most importantly, harvest losses are not counted as part of national production because the harvest has not been successfully produced.

Post-harvest losses are losses that occur to successfully harvested products. They share many of the same mechanisms as harvest losses, including damage during packaging, handling and transportation, exposure to improper temperatures during storage or transport, aggregation and storage for sale or processing, inadequate equipment and facility sanitation to protect from bacterial damage and inadequate protection from vermin.

[59] USDA and Science Company: https://www.sciencecompany.com/Methylene-Blue-Milk-Test.aspx

Most loss descriptions are around post-harvest losses, but pre-harvest and harvest losses are frequently even bigger. Potatoes, for example, are relatively hardy once harvested and properly cured. Proper curing is a key action as it greatly inhibits decay by bacterial processes, and therefore makes the potato less sensitive to storage conditions than many other crops. Post-harvest losses for potatoes are reported to be about 2 percent in Madagascar. For this reason, it may seem unproductive to include potatoes as candidates for handling by cold chain equipment. However, harvest losses for potato farms can be as high as 60 percent of the potato crop the farmer tries to produce, and cold chain equipment in the form of proper refrigeration and humidity-controlled aggregation storage at the farm level can cut that post-harvest loss by 35 percent or more, thereby increasing total successful harvest by half again more than is currently possible. In addition to achieving proper curing at the start of the cold chain, it is further possible, through continued temperature and humidity control, to prevent the dehydration and shrinkage and sprouting typically seen in potatoes left sitting in bags in home pantries. Potatoes can be kept for up to a year in properly controlled conditions. Given the harvest is normally just in the first two months of the year, this makes potatoes available year-round. This may be important to prevent increased potato production that would result in a glut that lowers prices for the producers. An economic analysis at this level is beyond the scope of this report but should be undertaken for informed investment in the potato market.

Table 35. Analysis of harvest losses and return on investment for CCE

	Potato	Tomato	Fish	Dairy
Attempted Production (t/year)	402,012	60,539	653,622	171,817
Successful Production (t/year)	251,258	40,864	130,724	103,090
Total Harvest Losses (t/year)	150,755	19,675	522,898	68,727
Remaining Production after Farm Consumption (t/year)	226,132	36,777	117,652	99,121
Estimated Portion of Total Harvest Losses at Farm Level	60%	60%	80%	80%
Estimated Portion of Total Harvest Losses at Wholesale or Commercial Processing Level	2%	10%		8%
Estimated Portion of Total Harvest Losses at Retail Level	2%	2%	8%	
Economic Value (US$/t)	$440.63	$440.63	$3,084.39	$384.68
Loss Economic Impact (US$/year)	$66,426,467	$8,669,373	$1,612,818,657	$26,437,598
Potential Cooling Loss Prevention	37.50%	32.50%	70.00%	50.00%
Cold Chain Preventable Loss Value (US$/year)	$24,909,925	$2,817,546	$1,128,973,060	$13,218,799
ROI for 100% CCE (years)	**10**	**16**	**2**	**3**

Summary of Cold Chain Requirements and Costs

Average farms in Madagascar are 1.3 hectares.[60] This means individual production is small. However, it also means many farms are close enough to share larger, higher-quality chilling facilities. For example, during potato harvest in January and February, the average farm produces just 80 kg of potatoes. This is only a few sacks that will have the greatest shelf life if it is first cured in the correct temperature and humidity environment. Small, chest-size refrigerators can maintain a cool temperature but are not typically humidity controlled and thus do not optimize storage for product longevity. However, the small farms are close enough to make sharing larger units among several feasible. A larger solution was selected for ease of pricing and energy consumption evaluation, but it is possible to divide the devices into smaller units. The total required cooling capacities will not be changed by that, though energy demand is increased as smaller units tend to be less efficient.

Cooling is also most urgent for agricultural sectors where spoilage is most rapid. Dairy and fish are prime examples and are also the most immediate need identified. In addition to specific products, the analysis includes the energy and cost estimates needed to develop cold transportation. The model uses refrigerated trucks in the five-ton range that can move products from aggregating refrigerators at the production areas level to larger community cold storage units for distribution both to local markets and to move on to larger urban storage facilities and markets. This highlights the importance of road development to the successful moving of agricultural products by truck. While it is beyond the scope of this analysis to involve road development costs or proposals, it does suggest that where roads are being developed should improve the scoring of a potential refrigeration capacity installation, as it lowers transport success sensitivity and therefore increases the potential for the economic success of a cold facility installation.

Through this approach and following the method described above, the agricultural cold chain analysis is presented according to the two scenarios summarized in the section above. They are:

- Scenario 1 – 100 percent development of cold chain in all four value chains.
- Scenario 2 – 20 percent development of cold chain in all four value chains.

The cooling and related energy needs, followed by a summary of costs, for each scenario are presented for all four value chains.

Scenario 1

The total harvest in tons per value chain and the associated required cooling capacity in GWh/year for Scenario 1 is presented in Table 36. Note that the harvest tons consider the parametric evaluation of the product percentage available for cold chain storage at each point within the value chain.

[60] The Borgen Project, 10 Facts About Agriculture in Madagascar.

Table 36. Scenario 1 - summarized cold chain requirements and costs

Scenario 1	QTY in Cold Chain (minus self-consumed) in Tons/Year	Refrigeration Energy Demand in GWh/Year	Cold Chain Transport in t-km/year	Cold Transport Cost in USD	Capex Cost In USD	Per Capita Capex in USD
Potato	226,132	53	19,528,802	$1,712,114	$250,457,668	$9
Tomato	36,777	12	3,070,227	$269,171	$46,415,023	$2
Fish	117,652	33	2,101,738	$184,262	$2,394,974,101	$83
Dairy	99,121	115	1,024,541	$89,823	$37,092,598	$1
Totals	**479,682**	**212**	**25,725,308**	**$2,255,369**	**$2,728,939,389**	**$95**

Energy demand for Scenario 1 is estimated at 212 GWh/year and requires about 1.8 million liters of truck diesel fuel for refrigerated transport.

For energy requirements:

- It is assumed that there is no distributed grid power available at production locations and that off-grid solar power needs to be provided to these sites.
- It is assumed that the community-level systems also may require off-grid solar or grid-tied solar with backup batteries to handle demand during grid outages or brown-outs.
- It is assumed that large urban facilities and markets have distributed grid power and whether they require solar or battery backup systems will be determined on a case-by-case basis. In any event, these are commercially successful facilities already, so funding them for solar should involve at least some cost sharing and would not be a principal focus of grant money.

During the field mission to Madagascar, it was observed that most urban locations already have larger cold storage facilities, as do supermarkets and other shops, all of which are already operating on grid power. The grid's reliability is not fully satisfactory, however, and large losses occur periodically when a facility loses power, sometimes for days at a time. As such, using the methodology and assumptions presented in the section above, Table 37 provides the cold chain requirements for Scenario 1 in terms of tons/year required for cooling, the refrigeration power consumed in terms of GWh per year, and the requirements for cold transport in terms of tons-kilometer per year transported. These outputs will be used in the section below to estimate the required cooling costs.

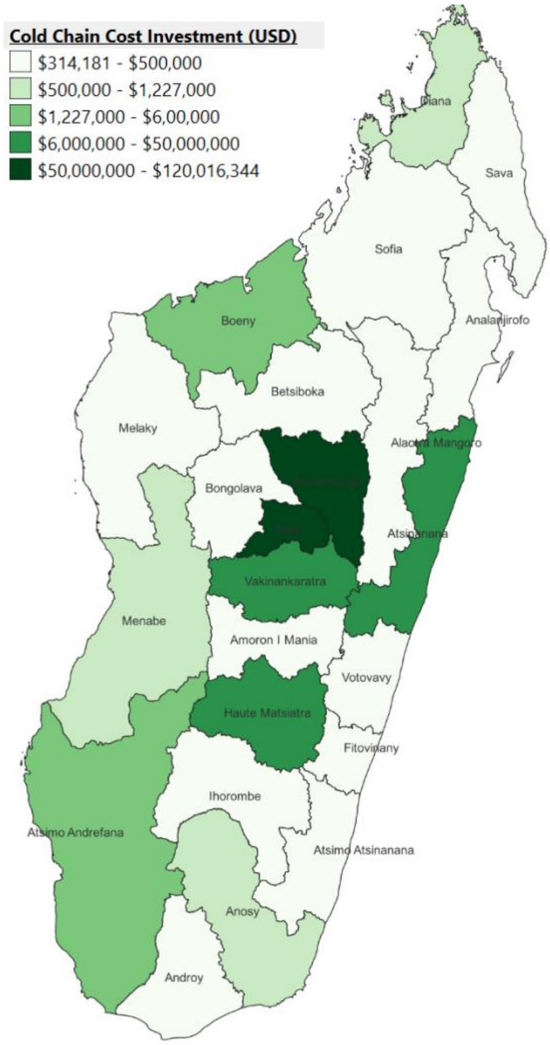
In addition, an analysis of the likely regional distribution of the energy demand requirements and associated cold chain costs was conducted for Scenario 1, presented in Table 38. The distribution of crop product takes into account data on crop yields collected during the field mission to Madagascar. Crop distribution estimates for potatoes and tomatoes are from 2020–2021 data, while fish distributions are from 2021, and dairy from 2020.

Table 37. Scenario 1 - crop production for cold chain target by region.

Region	Total Cooling Demand (MWh/Year)	Cold Chain Investment Cost (USD)
Alaotra-Mangoro	131 MWh/year	$9,692,77
Amoron'i Mania	31 MWh/year	$2,507,856
Analamanga	22752 MWh/year	$120,388,185
Analanjirofo	1076 MWh/year	$77,710,043
Androy	17 MWh/year	$1,549,866
Anosy	2401 MWh/year	$173,030,012
Atsimo-Andrefana	5581 MWh/year	$376,020,215
Atsimo-Atsinanana	91 MWh/year	$6,818,809
Atsinanana	2905 MWh/year	$20,126,823
Betsiboka	191 MWh/year	$14,003,732
Boeny	12835 MWh/year	$868,571,659
Bongolava	1 MWh/year	$352,379
Diana	5974 MWh/year	$430,010,733
Fitovinany	1 MWh/year	$352,379
Ihorombe	14 MWh/year	$1,310,369
Itasy	27159 MWh/year	$124,073,035
Matsiatra Ambony	10687 MWh/year	$62,078,467
Melaky	630 MWh/year	$45,617,390
Menabe	2311 MWh/year	$166,563,582
Sava	1186 MWh/year	$85,613,457
Sofia	420 MWh/year	$30,529,053
Vakinankaratra	154 MWh/year	$24,968,114
Vatovavy	683 MWh/year	$49,449,348

The estimate of cold chain investment requirements in USD, for all four value chains based on Scenario 1, by region are presented in the map below.

Figure 63. Scenario 1 - total cold chain investment requirements by region (USD)



Scenario 2

Table 39 presents the harvest/quantity estimated for cold chain based upon the assumption that 20 percent of the available product for cold chain will be implemented. Using this assumption, the cold chain for these four value chains will add 42 GWh/yr of energy demand at the completion of the 20 percent. Proportionally, vehicle diesel fuel will come in at 360,000 liters per year at this level. Table 39 also provides the Scenario 2 cold transport, cold chain equipment CAPEX investment requirements and the per capita CAPEX for each of the four value chains. Advantages to this scenario include manageable targets, smaller funding thresholds and allowing time for needed co-developments like road improvements to take place as the cold chain is being built.

Table 38. Scenario 2 cold chain requirements

Crop 20% Scenario	QTY in Cold Chain (minus self-consumed) in Tons/Year	Refrigeration Energy Demand in GWh/Year	Cold Chain Transport in t-km/year	Cold Transport Cost in USD	Capex Cost in USD	Per Capita Capex in USD
Potato	45,226	11	3,905,760	$342,423	$50,091,534	$2
Tomato	7,355	2	614,045	$53,834	$9,283,005	$0
Fish	23,530	7	420,348	$36,852	$478,994,820	$17
Dairy	19,824	23	204,908	$17,965	$7,418,520	$0
Totals	**95,936**	**42**	**5,145,062**	**$451,074**	**$545,787,878**	**$19**

While the total demands for cooling and cold chain links in a completed country-wide system seem relatively fixed, how their implementation is divided up is flexible. This means the links in the cold chain can be established separately, provided one does not build too far down the line in advance. For example, one can focus on the production site aggregation point facilities first, and locals will gain in terms of reduced spoilage and still be able to move products to local markets manually with less spoilage than currently occurs. Community-level cold facilities, however, do not become fully useful until refrigerated trucks are available to move produce from the aggregation points to the community storage. So, this second scenario involves creating a multi-year plan that focuses on production site cooling development first, followed by bringing in refrigerated trucks to take produce to the existing urban facilities, followed by a programme of building larger community facilities for smaller towns and large village markets. With objectives for 2030 and 2040, it seems reasonable to use these target dates for achieving different phases of the development of the agricultural cold chain links.

Recommendations for improvements in agriculture and fisheries cold chain

Strengthening the cold chain is a major opportunity to reduce agricultural production losses. Of particular importance are reducing post-harvest losses and improving transport infrastructure. A cold chain as applied to agricultural and food products can be defined as handling products within a temperature-controlled environment that extends the useful life at all points along the value chain.[61] The cold chain pathway includes pre-cooling, bulk storage, cooling during transportation, retail cooling and household refrigeration before consumption. Although a cold chain does not necessarily require all stages, it must involve at least one of these steps.

Madagascar faces several significant gaps in its agricultural cold chain, hindering the efficiency and effectiveness of the country's agricultural sector. Some of the key gaps include:

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[61] Kitinoja, L. 2013. Use of cold chains for reducing food losses in developing countries. Postharvest Education Foundation White Paper No. 13-03)

- **Electricity:** Access to stable electricity is a significant barrier to cold chain outcomes in Madagascar. Access to off-grid solar cold chain solutions may also provide an important tool in reducing post-harvest losses and increasing product values.
- **Infrastructure:** The lack of adequate cold storage and transportation facilities throughout the country poses a challenge for agricultural development and food security. Insufficient infrastructure limits the ability to preserve perishable agricultural products, leading to post-harvest losses and reduced shelf life. Limited access to reliable refrigeration and cold chain logistics impedes the distribution of agricultural produce from rural areas to urban centres and export markets.
- **Technology and Equipment:** Unavailable, unaffordable or inaccessible cold chain technologies and equipment further exacerbate the cold chain gaps. Modern refrigeration technologies, temperature-controlled transportation and cold storage solutions are necessary to maintain the quality and freshness of agricultural products. However, the cost of acquiring and maintaining such equipment can be prohibitive for many small-scale farmers and agribusinesses.
- **Education:** Lack or low level of rural women's education is also a barrier to pushing development and competitiveness of fresh vegetable value chains, and therefore of cold chain development
- **Awareness and Training:** Lack of awareness and technical know-how regarding cold chain management is another challenge. Farmers and stakeholders involved in the agricultural value chain may not be well informed about best practices for handling, storing and transporting perishable goods at optimal temperatures and market information. This knowledge gap results in avoidable losses and reduces the overall competitiveness of Madagascar's agricultural exports.
- **Financing and Investment:** Insufficient access to finance and investment opportunities limits the expansion and modernization of the agricultural cold chain. Encouraging both domestic and foreign investments in cold chain infrastructure is essential to strengthen the entire value chain, from production to distribution. Locally available finance is also a key consideration in the improvement of agricultural and fisheries cold chains – wherein financing and investment are oriented towards increasing access to locally available finance which in turn makes cooling solutions more affordable. However, this must go hand in hand with infrastructure improvements.

Addressing these gaps in Madagascar's agricultural cold chain requires a coordinated effort from the government, private sector, development partners and local communities. By investing in infrastructure, technology, education and policy support, Madagascar can enhance the efficiency and competitiveness of its agricultural sector, reduce harvest and post-harvest losses, improve food security and increase income for farmers.

In addition, because the implementation of cold chain integrity will set an example of what is possible, the first cold chain installations are recommended **to focus on areas where the financial value and adoption of new technology are most likely to be recognized and taken advantage of.** This is so the example set is most likely to be successful and, therefore, to foster the additional spread of cold chain technology. Agricultural cold chain investments should also be focused on the most immediate needs in these areas, which occur where spoilage is fastest – this prioritizes dairy and fish over most horticultural products for first adoption. As such, if Scenario 2 were adopted as the agricultural cold chain implementation plan, the first years would focus on these areas and later years on the horticultural areas, on the premise that adoption strategies will be seeded for the dairy and fish sectors by the work in the initial years.

Access to electrification for the operation of cold chain technology is pivotal for the development of agricultural value chains in Madagascar, particularly in remote and underserved areas. Electricity plays a crucial role in modernizing agricultural practices, enhancing productivity and fostering value addition through the operation of food processing and preservation activities.

- In the domestic market, temperature-controlled containers can improve the output and quality of the home-made cheese and yoghurt that a lot of dairy farmers depend on to take to market currently, as well as reducing bacterial deterioration of whole milk that can be sold for processing. Farm-level refrigerators can also mean farmers need to hold back a smaller percentage of their harvest for their own use because what they hold back no longer spoils easily.
- However, possibly the biggest single impact will be the addition of cooling equipment for smaller fishing operations, where losses can reach as high as 80 percent. The price of fish, per ton, is higher than the other agricultural products, so the ability to keep the fish fresh to sell has a higher financial impact per-unit energy of all the agricultural products and can produce the fastest return on investment (ROI), with absolute cash value return occurring in less than two years. As a result, such equipment should be a primary focus for initial investments.
- In addition to powering cold chain infrastructure, access to reliable electricity also enables the deployment of irrigation systems to reduce dependence on rain-fed agriculture and enable year-round cultivation that not only stabilizes food production but also allows for the cultivation of high-value cash crops. Electric-powered processing equipment, such as mills, food processors and cooking equipment, can also add value to agricultural products, leading to higher incomes for farmers and greater availability of processed goods for consumers.
- In the export market, electrification is vital for meeting quality standards and facilitating the operation of cold storage and processing facilities. These facilities are essential for maintaining product quality, extending shelf life and complying with international regulations, thus improving Madagascar's competitiveness in global markets. However, note that the fish export market has the most investment already, because of the cash value of fish. Subsidized investment in fish cooling should be focused on the domestic market and fisheries first and foremost.

CONCLUSION

The purpose of this task was to gather information on the overall immunization programme and the immunization cold chain in Madagascar, and to map the supply chain and cold chain equipment (CCE), including energy supply and health centre location, in order to develop a geospatial modelling framework that allows analysis of logistical costs, constraintsand challenges for the medical cold chain. The key results and takeaways of the analysis include the following:

- The cold chain equipment that is available is relatively new and should be functional for five to eight years as long as basic maintenance is provided.
- The majority of the basic health centres (CSBs) are using less than 10 percent of the cold chain capacity, indicating space for population growth, new vaccines and potentially less frequent deliveries. Most district stores have sufficient cold chain space, although some share the space with co-located hospitals.
- About 20 percent of CSBs do not have functional equipment and should be prioritized as new equipment is procured in order to extend immunization services to a wider population.
- As the energy grid expands and becomes more reliable, there should be close coordination with the immunization programme for procurement of new CCE if solar equipment is no longer necessary, reducing costs and streamlining the make and models of equipment in the country to facilitate maintenance.

The key results and takeaways of the agricultural cold chain analysis include the following:

- Agriculture is vital to the Malagasy economy yet there remain significant challenges and obstacles to the sector reaching its full potential and improving livelihoods.
- The poor quality of roads is a major barrier for safe transport of fresh perishable products from rural areas to urban areas.
- Return on investment (ROI) is fastest for fish, second fastest for dairy and slowest for other products – see Table 40.
- While the investments for tomatoes appear particularly unattractive, 70 percent of tomatoes can share equipment with potatoes, improving the economic feasibility of the investments for both products.

ANNEXES

Annex 1 - Indicative equipment and sizing per health facility

EQUIPMENT	QUANTITY CSB/DIS /MAT Size 1	QUANTITY CHD/SDSP Size 2	QUANTITY CHR/DRSP/CRNM Size 3	QUANTITY CHU/DPEV Size 4	UNIT POWER (Watts)	TOTAL POWER CSB/DIS/MAT	TOTAL POWER CHD/SDSP	TOTAL POWER CHR/DRSP/ CRNM	TOTAL POWER CHU/DPEV	HOURS USED PER DAY	ENERGY USAGE CSB/DIS/MAT Size 1	ENERGY USAGE CHD/SDSP Size 2	ENERGY USAGE CHR/DRSP/ CRNM Size 3	ENERGY USAGE CHU/DPEV Size 4
Lighting	1 ea.	40 ea.	120 ea.	120 ea.	*10.0 W*	10.0 W	400.0 W	1200.0 W	1200.0 W	*10.0 h*	100 Wh/day	4000 Wh/day	12000 Wh/day	12000 Wh/day
Exam Light	1 ea.	2 ea.	4 ea.	8 ea.	*20.0 W*	20.0 W	40.0 W	80.0 W	160.0 W	*2.0 h*	40 Wh/day	80 Wh/day	160 Wh/day	320 Wh/day
Microscope	1 ea.	3 ea.	5 ea.	5 ea.	*10.0 W*	10.0 W	30.0 W	50.0 W	50.0 W	*2.0 h*	20 Wh/day	60 Wh/day	100 Wh/day	100 Wh/day
Radio	1 ea.	1 ea.	1 ea.	1 ea.	*30.0 W*	30.0 W	30.0 W	30.0 W	30.0 W	*8.0 h*	240 Wh/day	240 Wh/day	240 Wh/day	240 Wh/day
Small Refrigerator for vaccine storage	1 ea.	0 ea.	0 ea.	0 ea.	*60.0 W*	60.0 W	0.0 W	0.0 W	0.0 W	*8.0 h*	480 Wh/day	0 Wh/day	0 Wh/day	0 Wh/day
Large Refrigerator for Vaccine Storage		1 ea.	3 ea.	3 ea.	*500.0 W*		500.0 W	1500.0 W	1500.0 W	*8.0 h*		4000 Wh/day	12000 Wh/day	12000 Wh/day
Autoclave		1 ea.	1 ea.	2 ea.	*630.0 W*		630.0 W	630.0 W	1260.0 W	*1.0 h*		630 Wh/day	630 Wh/day	1260 Wh/day
Fan		8 ea.	20 ea.	20 ea.	*80.0 W*		640.0 W	1600.0 W	1600.0 W	*10.0 h*		6400 Wh/day	16000 Wh/day	16000 Wh/day
Rotator/Mixer		1 ea.	2 ea.	2 ea.	*60.0 W*		60.0 W	120.0 W	120.0 W	*1.0 h*		60 Wh/day	120 Wh/day	120 Wh/day
Water Bath		1 ea.	2 ea.	2 ea.	*400.0 W*		400.0 W	800.0 W	800.0 W	*1.0 h*		400 Wh/day	800 Wh/day	800 Wh/day

EQUIPMENT	QUANTITY CSB/DIS /MAT Size 1	QUANTITY CHD/SDSP Size 2	QUANTITY CHR/DRSP/CRNM Size 3	QUANTITY CHU/DPEV Size 4	UNIT POWER (Watts)	TOTAL POWER CSB/DIS/MAT	TOTAL POWER CHD/SDSP	TOTAL POWER CHR/DRSP/ CRNM	TOTAL POWER CHU/DPEV	HOURS USED PER DAY	ENERGY USAGE CSB/DIS/MAT Size 1	ENERGY USAGE CHD/SDSP Size 2	ENERGY USAGE CHR/DRSP/ CRNM Size 3	ENERGY USAGE CHU/DPEV Size 4
Spectrophotometer		1 ea.	2 ea.	2 ea.	*63.0 W*		63.0 W	126.0 W	126.0 W	*1.0 h*		63 Wh/day	126 Wh/day	126 Wh/day
Dental Chair		1 ea.	2 ea.	2 ea.	*710.0 W*		710.0 W	1420.0 W	1420.0 W	*0.5 h*		355 Wh/day	710 Wh/day	710 Wh/day
Compressor		1 ea.	2 ea.	2 ea.	*370.0 W*		370.0 W	740.0 W	740.0 W	*2.0 h*		740 Wh/day	1480 Wh/day	1480 Wh/day
Centrifuge		1 ea.	1 ea.	1 ea.	*600.0 W*		600.0 W	600.0 W	600.0 W	*1.0 h*		600 Wh/day	600 Wh/day	600 Wh/day
Jet Sonic Cleaner		1 ea.	1 ea.	1 ea.	*45.0 W*		45.0 W	45.0 W	45.0 W	*2.0 h*		90 Wh/day	90 Wh/day	90 Wh/day
Computer		2 ea.	4 ea.	4 ea.	*120.0 W*		240.0 W	480.0 W	480.0 W	*4.0 h*		960 Wh/day	1920 Wh/day	1920 Wh/day
Cell Phone Charger		5 ea.	10 ea.	20 ea.	*5.0 W*		25.0 W	50.0 W	100.0 W	*4.0 h*		100 Wh/day	200 Wh/day	400 Wh/day
Amalgam Filling Machine		1 ea.	1 ea.	1 ea.	*80.0 W*		80.0 W	80.0 W	80.0 W	*1.0 h*		80 Wh/day	80 Wh/day	80 Wh/day
X-ray machine			1 ea.	1 ea.	*200.0 W*			200.0 W	200.0 W	*1.0 h*			200 Wh/day	200 Wh/day
CD4 counters			1 ea.	2 ea.	*200.0 W*			200.0 W	400.0 W	*4.0 h*			800 Wh/day	1600 Wh/day
Blood Chemical Analyzer			1 ea.	1 ea.	*45.0 W*			45.0 W	45.0 W	*6.0 h*			270 Wh/day	270 Wh/day

EQUIPMENT	QUANTITY CSB/DIS /MAT Size 1	QUANTITY CHD/SDSP Size 2	QUANTITY CHR/DRSP/CRNM Size 3	QUANTITY CHU/DPEV Size 4	UNIT POWER (Watts)	TOTAL POWER CSB/DIS/MAT	TOTAL POWER CHD/SDSP	TOTAL POWER CHR/DRSP/ CRNM	TOTAL POWER CHU/DPEV	HOURS USED PER DAY	ENERGY USAGE CSB/DIS/MAT Size 1	ENERGY USAGE CHD/SDSP Size 2	ENERGY USAGE CHR/DRSP/ CRNM Size 3	ENERGY USAGE CHU/DPEV Size 4
Haematology Mixer			1 ea.	1 ea.	*230.0 W*			230.0 W	230.0 W	*4.0 h*			920 Wh/day	920 Wh/day
Air-Conditioning Unit			3 ea.	3 ea.	*1500.0 W*			4500.0 W	4500.0 W	*8.0 h*			36000 Wh/day	36000 Wh/day
Resuscitation machine				1 ea.	*165.0 W*				165.0 W	*4.0 h*				660 Wh/day
Incubator				1 ea.	*917.5 W*				917.5 W	*4.0 h*				3670 Wh/day
Prenatal Care Scale				1 ea.	*2.0 W*				2.0 W	*1.0 h*				2 Wh/day
Nebulizer				1 ea.	*85.0 W*				85.0 W	*4.0 h*				340 Wh/day
Oxygen Concentrator				1 ea.	*285.0 W*				285.0 W	*4.0 h*				1140 Wh/day
Suction Machine				1 ea.	*145.0 W*				145.0 W	*4.0 h*				580 Wh/day

Annex 2 - Scenario 2 of the medical cold chain analysis - CCE electrification

Scenario 2 assumes an alternative wherein only the CCE equipment of each heath facility is electrified. Under this scenario, the percentage of CCE as part of the total electricity needs per facility are used to estimate the required system sizing and cost, which are shown again in Table 41.

Table 39. Electrification of requirements only

	Size 1 CSB/DIS/MAT	Size 2 CHD/SDSP	Size 3 CHR/DRSP/CRNM	Size 4 CHU/DPEV
% CCE consumption	54.5%	21.2%	14.0%	12.8%
CCE only System Design (kWh/day)	0.75	6.24	18.7	18.7
Off-grid Cost USD	$669	$5,743	$16,495	$16,495
Hybrid Cost USD	$669	$3,297	$9,157	$9,157

Using the input assumption for the CCE electrification only, the tables below present the hybrid system costs for those facilities that are planned to be on grid (JIRAMA or MV mini-grid) as well as those that will require off-grid, independent solar PV systems.

Table 40. CCE electrification only - size and budget of hybrid healthcare facilities

Size	Type of Facilities	Dimensionnement du système hybride			Facilities on grid (2023)	Future electrification modality		Total Cost
		Energy Consumption kWh/day	PV Array Size (kWp)	Grid Expansion		Extension du réseau	Mini-réseau MV	
1	CSB1	0.7	0.3	$669	56	75	132	$175,947
1	CSB2	0.7	0.3	$669	182	152	204	$359,922
1	DISP/MAT	0.7	0.3	$669	1	0	0	$669
2	CHD	6.2	1.8	$3,297	-	-	-	$0
2	SDSP	6.2	1.8	$3,297	43	25	10	$257,176
3	CHR	18.7	5.3	$9,158	2	1	0	$27,473
3	CHRD	18.7	5.3	$9,158	15	16	5	$329,674
3	CHRR	18.7	5.3	$9,158	4	2	0	$54,946
3	CRNM	18.7	5.3	$9,158	1	1	0	$18,315
3	DRSP	18.7	5.3	$9,158	15	4	0	$173,994
4	CHU	18.7	5.3	$9,158	5	0	0	$45,788
4	DPEV	18.7	5.3	$9,158	1	0	0	$9,158
4	Hosp	18.7	5.3	$9,158	2	0	0	$18,315
	Total				**327**	**276**	**351**	**$1,471,377**

Table 41. CCE electrification only - size and budget of off-grid healthcare facilities

Size	Type of Facilities	Off-Grid Standalone System Sizing			Future electrification modality		Total Cost
		Energy Consumption kWh/day	PV Array Size (kWp)	System Cost	LV Mini-grid	Standalone SHS	
1	CSB1	0.7	0.3	$669	74	706	$521,820
1	CSB2	0.7	0.3	$669	102	1102	$805,476
1	DISP/MAT	0.7	0.3	$669	0	0	$0
2	CHD	6.2	1.8	$5,743	0	1	$5,743
2	SDSP	6.2	1.8	$5,743	1	35	$206,753
3	CHR	18.7	5.3	$16,496	0	0	$0
3	CHRD	18.7	5.3	$16,496	1	22	$379,399
3	CHRR	18.7	5.3	$16,496	0	3	$49,487
3	CRNM	18.7	5.3	$16,496	0	1	$16,496
3	DRSP	18.7	5.3	$16,496	0	4	$65,983
4	CHU	18.7	5.3	$16,496	0	0	$0
4	DPEV	18.7	5.3	$16,496	0	0	$0
4	Hosp	18.7	5.3	$16,496	0	0	$0
	Total				**178**	**1874**	**$2,051,157**

Annex 3 - Summary of field mission meetings

Table 42: Summary of meetings during field assignment

Areas and number of days spent	Number of meetings	Type of organizations	Number of meetings with women	Type of value chain
Antananarivo (6 days)	13	Ministry of Energy, MINAE Industry Ministry, WFP, AFDB), supermarket, cold room maintenance company, Fishing company	7	Fisheries,potato,tomato, dairy
Vakinankaratra (4 days)	8	MINAE, farmers' cooperative, retail market, dairy companies, vegetables company	7	Fisheries,potato,tomato, dairy
Amoron'I Mania (2 days)	6	MINAE, farmers' associations, FAO, market	6	Potato
Itasy (1day)	7	MINAE, Industry Ministry, dairy company, dry fruits and vegetables company, processed tomato company, fisheries cooperative, fish market, potato wholesalers' market.	2	Potato, tomato, fisheries, dairy

Annex 4 - Refrigeration Load and Sizing Requirements Methodology

The initial worst-case evaluation is based on determining the cost of implementing an ideal cold chain for Madagascar based on annual production. This involved assuming the use of standard commercial equipment for refrigeration and transport, with the refrigeration powered either by solar or grid power and transport operating on diesel or petrol fuel, and then scaling that to a more realistic 20 percent implementation number so that duplication of existing facilities is avoided, and more practical costs and timing become possible. After the ideal scenario, alternative technologies and approaches are described that can reduce costs.

Refrigeration load is determined based on all production measured in metric tons, except with some conversion to liters for milk. For each product, the following information is extracted from documents made available by Madagascar's agriculture ministry, USDA information and various commercial sources cited in the value chain-specific section:

- Annual harvest quantities t_A in metric tons. Milk data are sometimes reported in liters or kiloliters. To convert liters to metric tons, an average milk density of 1.0309 gm/cc is used (source: US NIH, PubMed https://pubmed.ncbi.nlm.nih.gov/32726926/)
- Harvest field (or ocean water for fish) temperature T_H
- Storage or curing temperature to be achieved, T_S
- Simple Specific Heat Capacity, *c*, of each value chain item evaluated in joules (or megajoules)
- Average Heat of Respiration, H_R for vegetation, for each value chain item in joules/day
- Bulk density, ρ_B, in metric tons per cubic m (t/m³) of each value chain item was evaluated to determine required storage space
- Optimal relative humidity (RH) for storage or curing is noted for the design of the refrigerator cooling system and to determine whether or not humidification or dehumidification is additionally necessary.

Calculations:

Payload Heat Load in Watts to cool down, $W_C = (T_H - T_S) \times c + H_R / 86400$ s/day

Payload Heat Load in Watts to store, $W_S = H_R / 86400$ s/day

Refrigerator payload hold volume, $V_P = t_A \times \rho B$

Volume allowance for walk-in refrigerator aisle and circulation space, $V_{walk\text{-}in}/ = V_P \times 2$

Refrigerator box heat load allowance: This is a simplified approximation using cube-shaped refrigeration boxes and 150 mm foamed-in-place PU foam with thermal conductivity of 0.0262W/m³ (Rpf 5.5/in in the US system, taken from analysis of 150 mm wall panels (the maximum general thickness available for efficiency). This resulted in a box load of $W=(T_H - T_S) \times 1.0316 \times (V_{walk\text{-}in})^{⅓}$. Door opening loads were then set equal to one-tenth the box load, which is a common approximation for a unit not being constantly opened and closed all day, and assuming a high-grade strip curtain just behind the door to reduce cold air spillage when the door is opened.

The above load then has a safety factor of 20 percent added to allow for the accumulation of dirt on coils between standard maintenance cleanings.

Annex 5 - Cold Transportation Cost Basis

	Farm to Regional	Regional to Urban	Urban Central to Retail
Distances	30 km	200 km	20 km
Average Ex-factory Refrigerated Truck Cost China	$3,000.00/t	Ar 13,616,970.6000[1]	
Average Distance Covered Per day	50 km/day	91250 T-km/truck[2]	
Average Truck Life Expectancy	5 years		
Cost of Truck, Its Operation, Maintenance and Fuel	$1,600.00/year/t	Ar 7,262,384.3200/year/t[5]	
Maintenance Cost	$0.09 km-t	Ar 397.9389/km-t[4]	
Total Needed Cold Transport	61292243 t·km/year[5]		
Total needed Trucks	672		
Truck Capex based on 5T trucks	$10,075,437.13		

[1]Based on pricing for Chinese equipment on Alibaba at the time this file was created

[2]Based on observation in couintry by Guy Kodjogbe

[3]Based on industry information and adjusted for Madagascar fuel prices at the time this file was created

[4]Calculated

[5]From Cumulative Trans