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MADAGASCAR

Integrated Energy Access Planning

ELECTRIFICATION REPORT

JUNE 2024

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ABBREVIATIONS

ADER	Rural Electrification Agency (Agence de Développement de l'Electrification Rurale)
AFD	French Development Agency (Agence Française du Développement
AfDB	African Development Bank
ARELEC	Regulatory Electrification Authority (Autorité de Régulation de l'Electricité)
ESMAP	World Bank Energy Sector Management Assistance Program
EU	European Union
FNE	National Electricity Fund (Fond National de l'Electricité)
FNED	National Sustainable Energy Fund/Fonds National de l'Énergie Durable
GEAPP	Global Energy Alliance for People and Planet
GHI	Global Horizontal Irradiation
GIS	Geographic information system
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GLCEP	Geospatial Least Cost Electrification Plan
GIS	Geographic information system
GLCEP	Geospatial Least-Cost Electrification Plan (Analyse des options d'électrification géospatiale au moindre cout)
GoM	Government of Madagascar
IEP	Integrated Energy Plan
INSTAT	National Office of Statistics (Institut National de la Statistique)
IPP	Independent Power Producer
HV	High Voltage
JIRAMA	Jiro sy rano malagasy is the Malagasy public electric utility
JSI	John Snow Inc.
KV	kilovolt
kVa	Kilovoltampère
kW	Kilowatt
kWh	Kilowatt per hour
kWp	Kilowatt peak
LEAD	Least-Cost Electricity Access Development Project
LCOE	Levelized Cost of Energy
LV	Low Voltage
MECS	Modern energy cooking services
MEH	Ministry of Energy and Hydrocarbons (Ministère de l'Energie et des Hydrocarbures)
MINAE	Ministry of Agriculture and Livestock (Ministère de l'Agriculture et de l'Elevage)
MV	Medium Voltage
NEP	New Energy Policy (Nouvelle Politique de l'Energie)
ORE	Electricity Regulatory Authority (Office de Régulation de l'Electricité)
OSM	Open Street Map
PDMC	Least-Cost Power Development Plan (Plan de Développement au Moindre Coût)
PRIRTEM	Power Transmission Network Reinforcement and Interconnection Project in Madagascar
PUE	Productive Use of Energy
PV	Photovoltaic
RIA	Interconnected Antananarivo Grid / (Réseau Interconnecté Antananarivo)
RIF	Interconnected Fianarantsoa Grid / (Réseau Interconnecté Fianaranstoa)
RIT	Interconnected Toamasina Grid / (Réseau Interconnecté Toamasina)
SEforALL	Sustainable Energy for All
SDG	Sustainable Development Goal
SSA	Sub-Saharan Africa
SSS	Standalone Solar System
UEF	Universal Energy Facility
UN	United Nations
UNDP	United Nations Development Program
UNIDO	United Nations Industrial Development Organization
USAID	United States Agency for International Development
WWF	Worldwide Fund for Nature

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.

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

Cooking devices/Cooking appliances: Refers to a device and/or appliance regardless of fuel associated, e.g., “cookstove” or “pressure cooker”.

Cooking technologies: Refers to 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.

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 low voltage (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 a medium voltage (MV) line extension longer than 500 meters to interconnect one or more transformers, and to include a LV distribution network from each transformer through which consumer connections can be made.

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: Grid extension refers to 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 to connect 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 in this analysis.

Isolated grids: Existing non-interconnected national utility 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 that is used by consumers. LV networks in Madagascar are energized at 400 volts. Madagascar's network code defines LV as any voltage below 1,000 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 35 kV, 20 kV, 15 kV and 5 kV voltage levels. Madagascar's network code defines MV as any voltage between 1,000 and 50,000 volts.

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 including: 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.

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

On-grid: Service provided by JIRAMA via a combination of national electricity networks and smaller isolated generation-distribution systems.

Power transformers: Power transformers transform HV (50 kV or higher) to MV levels – usually 35, 20, 15 or 5 kV as an integral part of a grid substation.

Solid fuel: A fuel in a solid form that is used as a source of energy to produce heat or electricity, e.g., “wood, coal, charcoal, and peat”.

Substation: A facility that includes transformers, protection and coordination equipment, switches and gantries, whose purpose 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.

Time-Of-Use (TOU): The principle of adjusting the price of electricity for different periods of the day, typically to better reflect costs of generation during high-demand and low-demand periods.

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, which are larger pieces of equipment 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 provides 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.

[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).

MADAGASCAR IEP OVERVIEW

The Madagascar IEP results are derived from a detailed geospatial analysis that uses a dynamic geospatial modelling framework. The geospatial modelling framework will integrate data from numerous sources including JIRAMA generation-distribution network infrastructure data and characteristics, road networks, hydrologic data, population and demographic data, clean cooking data, health centre and vaccine infrastructure data and agricultural production and value chain data, among others. The geographically referenced data will be used to evaluate electrification, cold chain and clean cooking solutions for all urban, peri-urban and rural communities in Madagascar.

This ambitious project builds upon experiences from previous SEforALL integrated energy planning projects in Nigeria (2021) and Malawi (2022). The Madagascar IEP includes the following goals and objectives:

- Prepare and present a gender-responsive integrated energy plan that synthesizes a least-cost geospatial electrification approach to service expansion building on the recently completed electrification analyses undertaken in 2018 and 2021[7] to evaluate the least-cost pathway to universal electrification in Madagascar. The IEP places a particular emphasis on electrification of public facilities and opportunities to enhance productive use potential using existing and new data on affordability analysis. The electrification modelling framework will evaluate technology options based on least-cost supply, resulting in **an actionable list of grid expansion, mini-grid and standalone solar projects** – not just indicative estimates of access. The list of projects, taken together with technology cost analysis, is used to evaluate financing requirements by technology and by geographic area within Madagascar. This is an important advancement in electrification planning that has yet to be applied in Madagascar.

- Prepare a geospatial clean cooking model to promote the adoption of improved and modern energy cooking services throughout Madagascar. This analysis includes the introduction of improved cooking devices, alternative biomass fuels and/or electricity for traditional cooking fuels. The integrated electrification and clean cooking analysis will be prepared on a common geospatial information system sharing 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 geospatial models to evaluate logistical costs, constraints and challenges for both medical and agricultural cold chains. The models will incorporate medical cold chains for routine vaccinations, COVID-19 vaccinations and future vaccination needs as well as analysis of agricultural cold chains to assess the magnitude, energy demand and total cooling cost of selected agricultural products such as fish, dairy and other temperature-sensitive produce or agricultural products. The cold chain analyses will be incorporated into the electrification and cooking models to identify areas where

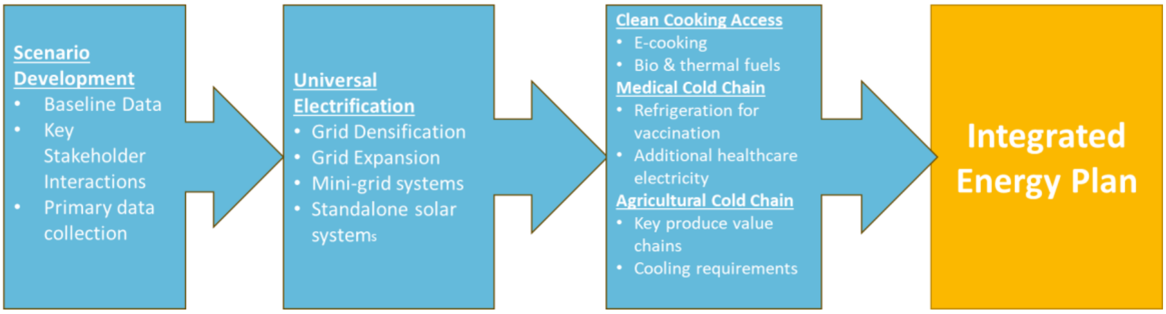
[7] Assistance Technique a la Préparation d'une analyse des options d'électrification géospatiale au moindre cout pour un déploiement sur réseau et hors réseau Madagascar, Rapport Finale. World Bank, August 2021.

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 targeting 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.

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

Figure 1. IEP development flow chart



Purpose of this report

This report presents the IEP electrification plan. It begins by describing the electrification challenge in Madagascar, then a discussion of the methodology used to develop the IEP. The methodology begins with a summary of the data collection and validation process, followed by a discussion of the basis of the geospatial modelling framework. The methodology is followed by a presentation of the results of electrification modelling, sensitivity analyses and electrification financing requirements. The last section of this report presents conclusions and considerations for the next stage of IEP implementation.

ELECTRIFICATION IN MADAGASCAR: OVERVIEW AND CHALLENGE

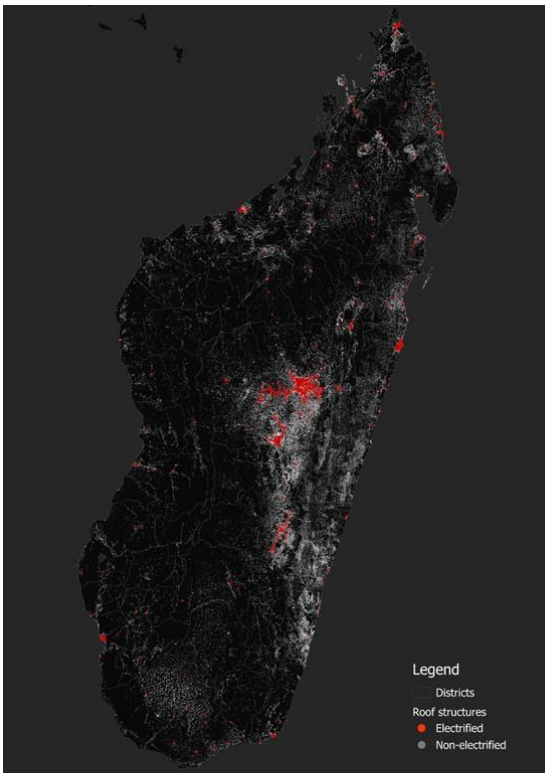
The Access Challenge

While the electrification rate in Madagascar has been estimated at 35 percent,[8] definitive statistics on urban and rural electrification rates are not available. The World Bank estimates that over 18 million people currently lack electricity access in Madagascar, ranking thirteenth in terms of the size of the unelectrified population worldwide.[9] Table 1 provides an overview of the estimated connections by electrification modality in 2023, while Figure 2 provides a visual representation of the electrified versus non-electrified areas of the country.

Table 1. Estimated 2023 connections
(Source: JIRAMA, ADER and MTF 2023)

Modality	Estimated 2023 connections[10]
JIRAMA Existing Customers	620,839
Mini-Grids	50,882
Standalone solar	1,260,000
Totals	**1,931,721**

Figure 2. Estimated electrified versus non-electrified areas in Madagascar
(Source: IEP 2023)



Ministry of Energy and Hydrocarbons: Electrification Policy

The Ministry of Energy and Hydrocarbons (MEH) has the statutory responsibility for establishing and overseeing electrification policy, conducting strategic planning, and facilitating electrification investment. The 2015–2030 National Energy Policy (NEP), developed with support from the European Union, sets a target of 70 percent access by 2030. To operationalize the NEP, the World Bank financed development of a least-cost electrification plan in 2021, referred to as the Analyse des options d'électrification géospatiale au moindre cout (GLCEP), whereas the Plan de Développement au Moindre Coût (PDMC) provides studies on demand, and the generation and transmission plan. MEH is currently updating the NEP that will be referred to in the future as the Plan d'Emergence Energétique.

[8] In 2020, Tracking SDG7 report (2023).

[9] World Bank, April 2023 (see link).

[10] This estimate represents all connections, in the case of JIRAMA consumers the 2022 JIRAMA commercial data showed a total of 620,839 consumers, and the standalone solar estimates are derived from the Madagascar MTF survey, which estimates solar use at 1.26 million (drawing from approximately 20 percent of households having some form of solar standalone system).

MEH supervises JIRAMA (the utility), the Agency for the Development of Rural Electrification (ADER), and the Electricity Regulatory Authority (ORE) (the regulator). A decree issued in March 2023 directs JIRAMA to regularize service areas by production site. The intention of this decree is to define limits of JIRAMA service areas that in turn provide enhanced clarity for private investment in mini-grids. MEH has also initiated a programme to strengthen ADER through which it will hire and train staff to support electrification investment at the regional level and to enhance use of the National Fund for Sustainable Energy (FNED) once it becomes operational.

JIRAMA: Grid Service

JIRAMA is the Malagasy state-owned electricity and water service provider. JIRAMA operates a series of generation-distribution service networks that serve major population centres. JIRAMA-owned and operated networks include three separate transmission-distribution networks that serve Antananarivo (RIA), Toamasina (RIT) and Fianarantsoa (RIF). JIRAMA also operates 94 smaller, isolated generation-distribution systems that provide service to smaller towns throughout the country. In total, JIRAMA serves 620,839 customers (2022), of which 587,429 or 95 percent are residential. New connections vary year to year, primarily due to available funding, with as many as 35,186 new connections in 2018 and as few as 13,737 connections reported in 2022. Overall, 100,501 consumers were connected between 2018 and 2022, at a rate of about 20,000 per year. JIRAMA has not yet developed a distribution master plan, nor has it developed a geospatial information system. JIRAMA planning is focused primarily on power supply expansion, transmission expansion and installation of revenue meters for all connected consumers.

JIRAMA operates under significant financial distress given that tariff levels are far below the cost of service. In addition, JIRAMA suffers from high losses, low revenue collection rate and inadequate resources to address these operating conditions. As reported by AfDB[11] JIRAMA's collection rate was approximately 60 percent in 2018. For its part, JIRAMA estimates losses at 30 to 35 percent[12] of which approximately 10 percent is attributed to technical losses and 20–30% is attributed to commercial losses and theft. JIRAMA officials noted that the interconnected distribution networks of RIA, RIT and RIF are heavily loaded relative to [13]. SAIDI or SAIFI metrics but these have not been evaluated to provide a clear understanding of power reliability, nor have load flow studies been performed to evaluate power-quality issues. However, studies are carried out on an ad hoc basis according to demand. Discussion with JIRAMA revealed that power quality and reliability are recognized challenges by JIRAMA management in the three larger grid systems and multiple smaller isolated grids.

With respect to tariffs, JIRAMA received authorization to increase its tariff in 2017, 2018, 2021[14] and again in January 2023. The JIRAMA 2022 customer database indicates that JIRAMA charged an average of MGA 550 per kWh or USD 0.12 per kWh for all customer categories. This is equivalent to roughly half of the cost of generation[15] based on data from an earlier study.[16]

[11] AfDB, Green Mini-Grids, 2018.
[12] Stakeholder Interview with JIRAMA, 2023.
[13] JIRAMA planning officials consultant interview, May 2023.
[14] With the change to OPTIMA tariffs for the "Residential" categories.
[15] AfDB, Green Mini-Grids, 2018.
[16] GIZ, Opportunities for Solar Business in Madagascar, 2016.

Given that tariffs are below the cost of service, JIRAMA has no financial incentive to greatly expand connections.

Overview of major grid infrastructure development projects

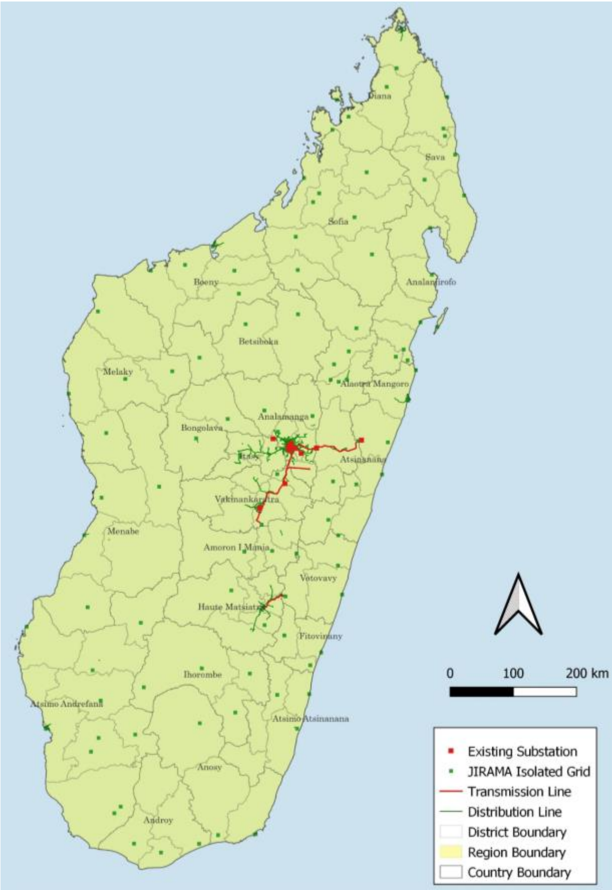
While JIRAMA will require significant reforms, such as significant tariff increases, and/or decreases in its cost of production particularly for its isolated grids, to reach financial viability (see the JIRAMA Recovery Plan for more information), investments from the AfDB, Korean Exim Bank, European Investment Bank and KfW are supporting expansion of JIRAMA transmission facilities over several phases including a project referred to as the Power Transmission Network Reinforcement and Interconnection Project in Madagascar (PRIRTEM). The first phase is designed to interconnect the RIA and RIT distribution networks with a 267 km 220 kV transmission and to build four new grid substations at a cost of approximately USD 200 million. The second phase will include a 135 km 220 kV transmission line between RIA and Anstirabe, linked to a separate project for the construction of the 192 MW Sahofika hydropower station. It is understood that PRIRTEM Phase 1 is about to start construction work, but that Phase 2 depends upon agreements between the Sahokifa developer consortium and project financiers. Both phases of the PRIRTEM project also include small rural electrification components focused on grid extension and small hydro-powered mini-grids. A final Tana Medium Ring project is also proposed to strengthen RIA and RIF transmission networks (creating eight substations around Tanà and Antsirabe, and nearly 200 km of 90 kV transmission lines). This new project is designed to alleviate the saturation of the RIA and accommodate the solar energy generation projects currently being developed and expected in the short term. The transmission network scheme proposed in the PAGOSE project is also entering its final preparatory phases. Procurement and work will begin shortly to loop the transmission network into the RIA, with the renewal of various substations.

In addition, two World Bank-financed projects will also have a major impact on grid infrastructure and service delivery in Madagascar in the coming years. The upcoming Digital and Energy Connectivity for Inclusion in Madagascar Project (DECIM) will contribute to doubling energy access to 67 percent in Madagascar.[17] although the specific delivery modalities are yet to be finalized. The ongoing World Bank financed Least-Cost Electricity Access Development (LEAD) project will install approximately 195,000 new low-cost grid connections using ready board technology between 2023 and 2024, in addition to 52,000 connections that will be financed by JIRAMA between 2023 and 2028. All told, this will result in 247,000 new connections through 2028 or about 41,000 connections per year, approximately double the current pace of JIRAMA expansion. JIRAMA reports that the new consumers will primarily be served through densification efforts (90 percent of new connections), and mainly in the RIA-grid served area. That is, grid expansion will not represent a significant percentage of new connections, so most of the new consumers will be served in urban and peri-urban areas in the existing JIRAMA service territory.

[17] World Bank, April 2023. See link for more information. https://www.worldbank.org/en/news/press-release/2023/04/07/madagascar-afe-set-to-expand-access-to-renewable-energy-and-digital-services-thanks-to-400-million-credit

Figure 3. JIRAMA interconnected network and isolated generation-distribution systems

(Sources: JIRAMA and ADER 2023)



ADER: Off-Grid Planning and Coordination

ADER was established to coordinate off-grid electrification planning as a supplement to efforts by JIRAMA to expand on-grid service, on behalf of the Government of Madagascar (GoM). ADER is primarily a planning and donor coordination agency that does not own or operate off-grid infrastructure. In addition to planning, it also coordinates efforts to expand private-sector implementation of off-grid investment for mini-grids and standalone solar solutions. ADER previously engaged in regional planning efforts for off-grid electrification and is currently developing mini-grid concession areas in distinct zones of Madagascar called Appels à Project (AP) zones, which are developed within the framework of the Indicative Regional Development Plan (PDRi), illustrated in Figure 4 below. The ADER mini-grid concession initiative includes a characterization of each AP and the communities (fokontany) the mini-grid concessions will serve. ADER plans to publish tenders that will solicit proposals from investors to develop mini-grids for the portfolio of projects. Approximately 1,876 projects are included in the AP database, although it is unclear how many if any have reached implementation.

The process that preceded this concession approach allowed private investors to present unsolicited proposals (via either the Appel à Candidature and Candidatures Spontanees approach) for mini-grid service areas. The concession approach will replace unsolicited proposals going forward.[18] While the AP mini-grid expansion methodology is sensitive and data-driven, most of the project sites in the AP database shared by ADER are quite small and thus may not prove to be attractive to private investors. However, it is understood that the goal of the AP process is to extend larger concession areas to attract further private-sector engagement, as well as further delineate JIRAMA's service territory from that of future private-sector energy service providers.

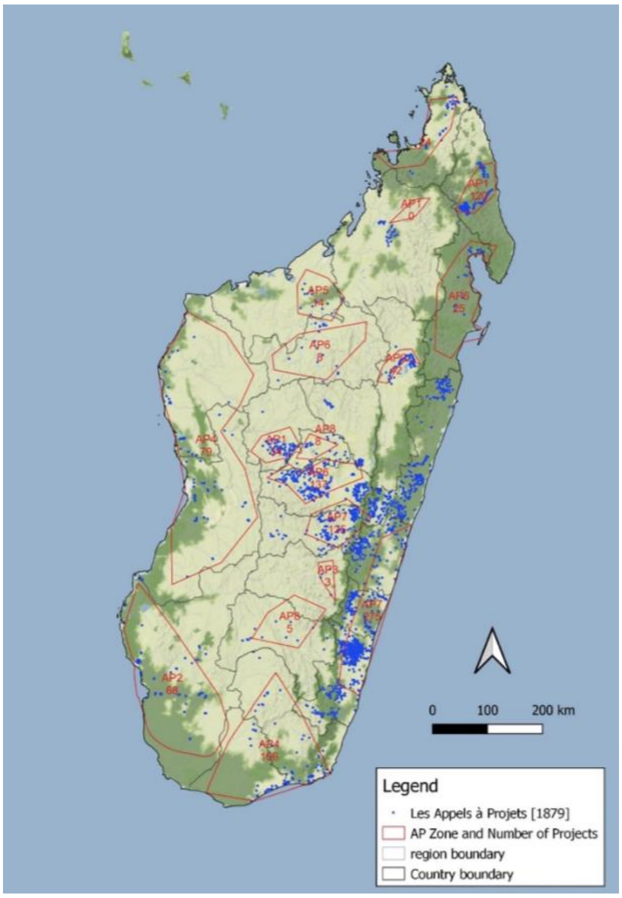


Figure 4. ADER's Appel à Projet zones

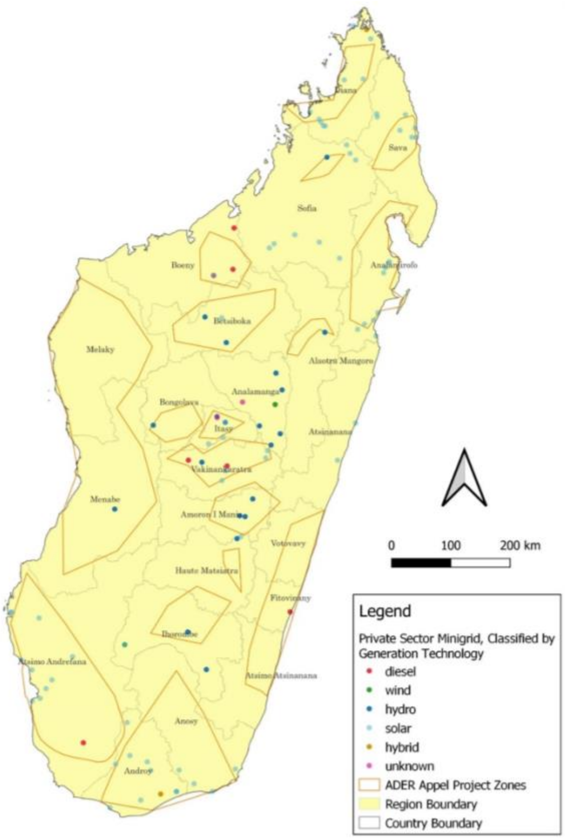
ADER operates with a team of three professionals responsible for project identification, analysis and design – a team that will need to expand as the off-grid programme grows. The entire ADER team is limited to just 27 positions so ADER will need to expand significantly to meet electrification expansion needs. ADER is establishing regional offices[19] with support from the World Bank and AFD, to have improved capability to collect data locally, to perform project oversight duties and to coordinate more effectively for planning and private-sector collaboration in the future. At present, ADER mainly operates from its office in Antananarivo.

ADER's functionality is currently limited to planning and off-grid coordination, but it also works with JIRAMA on grid extension projects in certain cases; it does not have an investment budget to support project development or funds to provide financial incentives to private investors. The GoM plans to establish a new fund, the National Fund for Sustainable Energy (FNED) that will replace the National Fund for Electricity (FNE) once it is operational. The FNE was designed to provide grants to support off-grid investment, and reportedly financed 20–25 diesel mini-grids some years ago. Finally, several development partners (the World Bank (WB), the French Development Agency (AFD), GIZ, EU, KfW, among others) are currently working with ADER on reinforcing the AP approach and increasing the attractiveness of the proposed concessions.

[18] It is understood that unsolicited proposals will still be allowed, but current regulations indicate that they should be 'exceptional' and are not the favoured approach.

[19] Six ADER regional offices operational in 2023, located in the regions of: Sava, Diana, Atsimo Andrefana, Atsinanana, Amoroni'mania and Anosy. These offices were financed by the LEAD programme supported by the World Bank. Two additional regional offices (Menabe and Melaky) are expected to be in place in early 2024 financed by AFD.

Figure 5. Private-sector min-grids as of 2023 (Source: ADER)



Private Off-Grid Service Providers

Several private off-grid service providers operate mini-grid systems throughout Madagascar. Table 1 provides a summary of the mini-grids organized by operator name as listed in the ADER database. In total, ADER reports that private service providers operate mini-grids in 107 communities that serve a total of 50,822 consumers as of May 2023. The total installed capacity for these 107 mini-grids is 14.7 MW; the average installed capacity is 85 kW for diesel generation, 261 kW for hydropower plants, and 202 kW for PV arrays. Figure 5 shows the locations of the existing private-sector mini-grids in 2023.

Table 2 also shows that these mini-grids serve 475 consumers on average, but solar PV systems serve an average of 150 consumers. ADER also reports that tariffs average approximately USD 0.50 per kWh in these mini-grids.

Table 2. ADER's database of active off-grid providers (Source: ADER May 2023)

Operator Name	Number of mini-grid sites	Sum of connections	Total Installed Diesel Generation (kW)	Total Installed Hydropower (kW)	Total Installed Solar PV (kW)
3ERAE	1	70	-	12	
Africa Green Tech	1	195	-	-	120
AIDER	5	2,347	-	135	
ANKA	14	2,146	582	-	953
ASA	3	332	-	-	33
ASS FIHAMY	1	115	-	-	8
Ass Telorae Tea Fahazavagna (Ass TTF)	1	116	-	-	8
Association FAHAZAVANA	1	60	-	-	3
Association FIMJA	1	213	-	35	

Association MAZAVA	1	78	-	-	5
Autarsys & Metaplasco	9	5,049	235	-	519
AUTARSYS/ TANTELY MIARISOA	1	250	48	-	
AUTARSYS/TANTELY MIARISOA	2	487	42	-	30
BETC Nanala	1	-	-	100	
CASIELEC	2	580	224	-	90
CASIELEC*	2	250	42	-	
ECOGEMA	1	935	-	80	
EDM	1	400	96	-	
ENERGIE TECHNOLOGIE	2	250	29	-	30
Entreprise Toky Construction	3	388	-	-	33
ANKA (was EOSOL)	2	639	-	-	72
ERMA et JIRAMA	1	250	-	700	
HIER	6	4,196	557	2,330	6
MADAGASCAR LIGHT RAY	1	400	200	-	
MAD'EOLE	1	80	16	-	11
POWER & WATER	1	300	-	60	
SEEM	1	-	323	-	460
SERMAD	2	10	44	-	
SM3E	1	350	-	60	
SRAFI – Managed by a village assn.	1	-	-	60	
WE LIGHT	35	1,773	175	100	1,197
no name provided	4	8,075	113	4,691	143
Total	**107**	**29,722**	**2,726**	**8,363**	**3,647**

Mini-grid service providers are permitted to propose tariffs. That is, customers may be charged on the basis of electricity consumption or can be charged through fees based upon the level of service required. Mini-grid operators who generate with small hydroelectric powerplants apply tariffs based upon energy consumption that may be as low as USD 0.14/kWh. Other mini-grid operators charge consumers based on service bundles that vary according to the level of service and duration that consumers use electricity. For example, WeLight charges single-phase consumers by service bundles that vary between MGA 800 to 65,0000 for energy bundles that may be as low as 0.13 kWh valid for one day to 18 kWh valid for 30 days. Mini-grid tariffs follow a prescribed structure by the Regulatory Electrification Authority (ARELEC); service providers are asked to establish tariffs that suit their business model and costs of service.

ARELEC: Sector Regulation

The Autorité de Régulation de l'Electricité (ARELEC), which was renamed from the Office de Regulation de l'Electricité (ORE) through the 2017 Electricity Grid code, is the electricity sector regulator in Madagascar. Its role is to oversee power quality, set tariffs and regulate private-sector electricity service providers. Through the energy sector reform law published by the GOM under Law Number 98-032 (January 1999), electricity generation, transmission and distribution activities are open to private-sector operation and investment. Mini-grid service providers must seek ARELEC approvals before applying their tariff.

Standalone solar market

The standalone solar market in Madagascar is largely led by the private sector, which fills the access gap left by the limited access to interconnected and isolated JIRAMA grids throughout the country.[20] In 2018, it was estimated that nearly a million standalone solar products had been sold.[21] There are several key distributors in Madagascar including: Baobab+, Jiro-ve, HERi, Orange, Majinco, MadaGreen, Power Technology and others. It is important to note that both Orange and Telma (mobile telecom providers) have launched standalone solar product sales and are implementing pay-as-you-go (PAYG) solutions. However, as of 2019, most products sold were noted to be of low quality with only four solar distributors selling Lighting Global quality-verified (QV) products.[19] Lighting Global, which is now VeraSol, is an international certification of standalone solar products that have been tested to meet minimum quality and durability standards recognized by funding organizations in the off-grid solar industry.

Specific donor projects, such as LEAD and the Off-Grid Market Development Fund sponsored by the World Bank, have helped support private-sector companies to expand standalone solar sales by providing subsidies including results-based financing (RBF) and lines of credit. A specific initiative under LEAD is a solar lantern project that was launched by MEH called Projet Kits Solaires Sociaux à Caractère Purement Social. The purpose of the project is to provide solar kits to approximately 500,000 beneficiaries, providing a subsidized 15 W/6 Ap-hour battery (Multi-Tier Framework (MTF) tier 1) system at an affordable price not to exceed USD 25 per unit. Nevertheless, the costs of these systems are significantly higher, especially when factoring in

[20] The World Bank. 2019. "International Development Association Project Appraisal Document on a Proposed credit in the amount of SDR 107.9 Million (USD 150 Million Equivalent) to the Republic of Madagascar for the Least Cost Electricity Access Development (LEAD) Project".

[21] Energizing finance: Taking the Pulse 2019.

the customer acquisition and logistical costs of maintaining standalone solar equipment in rural areas.

For the purposes of the IEP, standalone solar consumers were estimated using results from the Madagascar MTF survey, which estimates solar use at 1.26 million connections (drawing from approximately 20 percent of households having some form of solar standalone system[22]), although many of these systems are in areas with overlapping electrification modalities, for example standalone solar systems (SSS) in households that are already served by JIRAMA. The anticipated lifespan of standalone solar products is three to five years, so it is anticipated that all the existing standalone solar currently operating in Madagascar will need to be replaced with VeraSol compliant tier 2 systems prior to the 2030 deadline to achieve the Sustainable Development Goals (SDGs) including SDG7.

[22] As a reference point the 'Projet Kits Solaires Sociaux à Caractère Purement "Social"' estimates that 22 percent of households use off-grid solutions, such as solar kits and lanterns, as the main source main source of electricity.

METHODOLOGY

The steps used to evaluate demand for electricity service and the means to provide the lowest-cost electricity service are summarized here and explained in greater detail in the sections that follow. The methodology to evaluate electricity demand and supply options begins with aggregation of demand by applying average electricity consumption based upon results of energy expenditure surveys, applied to digitized housing structures visualized from high-resolution satellite imagery. Clustered housing structures and the resulting electricity demand is then used to dimension transformers, route low voltage (LV) and medium voltage (MV) networks, and to evaluate off-grid solutions where mini-grids and solar standalone solutions prove to be the most cost-effective electrification modality. This modelling framework is designed to evaluate technology options based on least-cost supply, resulting in an actionable list of grid expansion, mini-grid and solar standalone projects. The list of projects, taken together with technology cost analysis, is used to evaluate financing requirements by technology and by geographic area within Madagascar. The steps in the process are summarized as follows:

Step 1: Data Collection

- Define and collect data
- Collect structure, road, population and cost data
- Integrate data into geospatial modelling framework

Step 2: Energy Expenditure Survey

- Collect data from northern, central and southern survey zones. Evaluate expenditure levels
- Using utility tariff and projected mini-grid tariff, estimate on-grid and off-grid demand
- Use demand estimates to inform clustering analysis

Step 3: Clustering: Aggregate Demand in Specific Geographic Areas

- Clustering is used to aggregate demand and to dimension transformers for grid expansion and distributed generation for mini-grids
- Clustering is evaluated nationwide using housing structure locations and demand estimates

Step 4: Distinguish between On-Grid and Off-Grid Projects

- Routing algorithm is used to define LV networks and then to define MV pathways.
- Project characteristics and incremental connection costs are aggregated for each project; consumers and costs are evaluated to optimize electrification costs.
- Results are collated in database

Step 5: Project Cost Analysis and Balancing of On-Grid/Off-Grid Portfolio

- Compile complete list of grid densification, grid expansion and off-grid costs
- Organize results by region & district
- Draft access, implementation, and financing requirements plan with annualized targets by region

The steps are explained in greater detail in the subsections below.

Data Collection

The initial tasks undertaken to prepare the model for geospatial electrification planning were data collection, validation and aggregation. Data collection included collecting existing spatial and non-spatial data from multiple sources that included: JIRAMA network data, road data, and administrative boundaries and population data, among others. ADER and JIRAMA both shared databases related to existing distribution system infrastructure, existing and planned mini-grids, consumer data, cost data and planning information.

Geospatial modelling was performed by collecting and evaluating geographically referenced data needed to characterize electricity, clean cooking and refrigeration requirements. A summary of the geospatial data provided by stakeholders includes:

- ADER: In May 2023 ADER provided JIRAMA HV, MV and LV network data for Antananarivo and Fianarantsoa networks. ADER also provided data for existing and planned mini-grids, as well as AP project sites. ADER also provided data for health centres, mobile phone towers, mines, roads, education facilities and rivers, among other spatial datasets. The date when the JIRAMA and public facility data was most recently updated is unknown, but it is presumed to have been collected in preparation for the GLCEP project in 2021.
- JIRAMA: While JIRAMA does not use a formal GIS, it shared KML and single-line diagrams (SLDs) for its Antananarivo and Fianarantsoa networks. JIRAMA also provided the 2022 consumer database for all JIRAMA networks as well as historical unit cost data for its 20 kV distribution network (from 2010). In addition, JIRAMA provided information related to generation and transmission expansion planning that will be carried out from 2025 to 2035 during implementation of the PRIRTEM project, Tana Medium Ring project, and other projects.
- World Bank Small Hydro Atlas and GLCEP: The World Bank-sponsored Small Hydro Atlas includes useful geospatial attributes such as a list of potential small hydro sites, existing thermal power plans and land-use data. With support from MEH, the consortium was able to obtain the geospatial output files in August 2023 and use the tables and maps within the final report as references.
- Administrative layers: Administrative boundaries were downloaded from the Humanitarian Data Exchange (HDX) portal. Administrative levels include administrative level 0 (country), level 2 (district), level 3 (commune), and level 4 (fokontany). Level 1 (region) will use an adapted UNIDO shapefile to spatially demarcate the 23 regions in Madagascar. Unfortunately, these layers were not available from INSTAT or FTM as official layers that could be publicly shared at the time of writing.

A table of the spatial resources used within the electrification modelling is presented in the Geospatial Modelling Framework section below.

In addition to these data resources, NRECA used housing structure data from Google Open Buildings[23], an open-source dataset. The NRECA GIS team downloaded Open Buildings data for structures and roads in Madagascar, see Figure 6 below. The database generated from the building structures indicates that there are 9,275,852 million structures in Madagascar.

The digitized structure data were used to visualize individual household locations and to evaluate the number of inhabited structures by comparing total structures with household projections using population data. These housing structure/household locations will thereafter be linked with results of energy expenditure projections to evaluate the distribution of demand for electricity, together with cost and consumption estimates.

Figure 6. Google Open Buildings and Roads for Madagascar (accessed in April/May 2023)

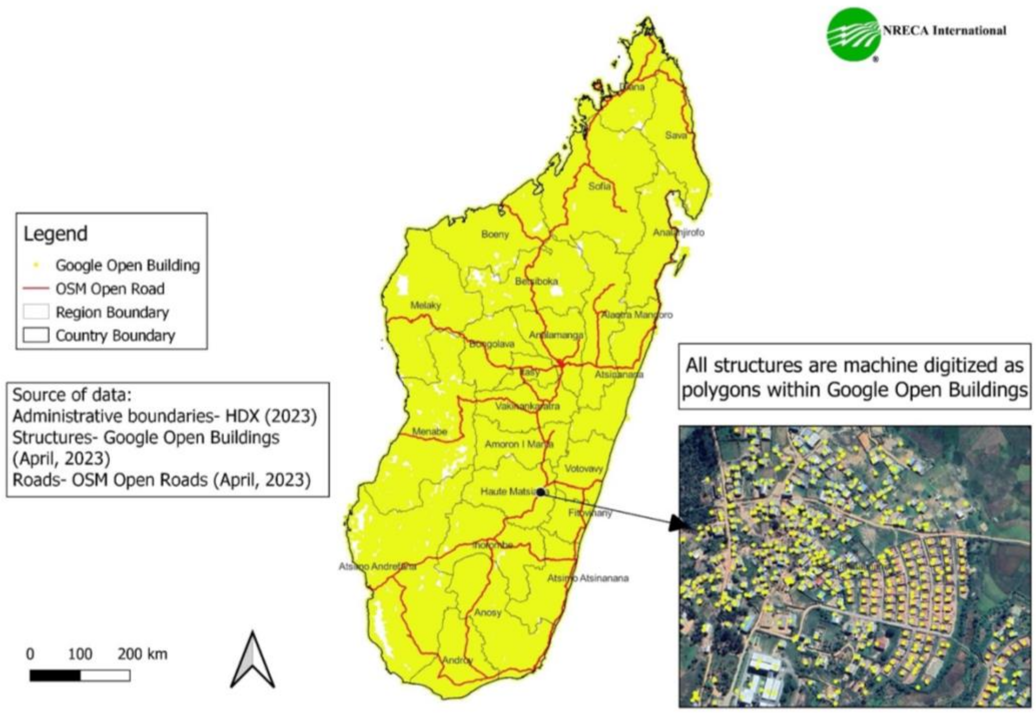
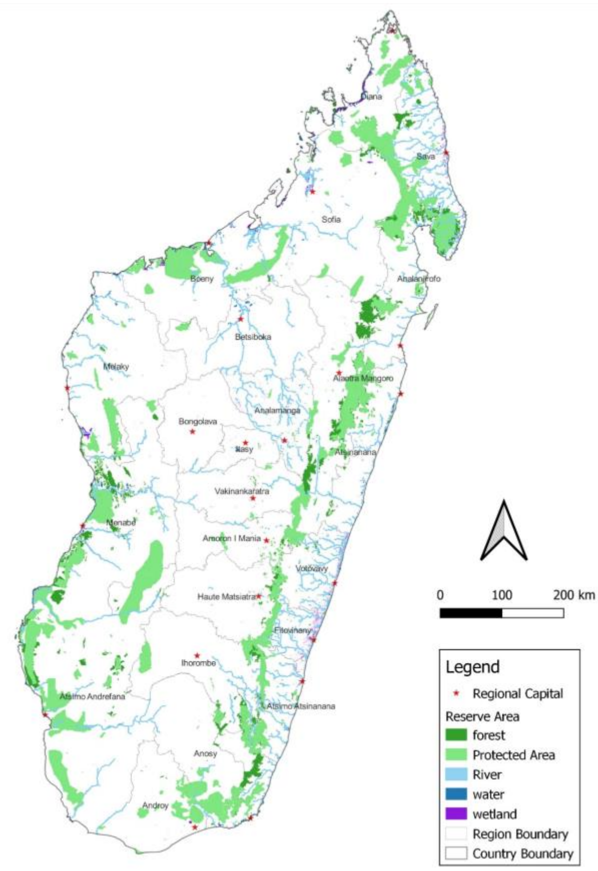


Figure 7. Major rivers, terrain attributes and protected areas
(Source: World Bank Small Hydro GIS Atlas 2017)

[23] See - https://sites.research.google/open-buildings/. Google Open Buildings dataset recency is determined by the availability of the high-resolution source imagery used to detect buildings. In Madagascar, the imagery varies depending on the location, but the majority of imagery is from 2020, with imagery around Antananarivo from 2022. The import data model is set with 70 percent confidence level with minimum 9 sq m area to be eligible to be designated as a structure point. Bing and OSM structure data layers were reviewed to cross check structure counts from GOB. GRID3 was not used as a potential source as only the settlement layer was available for GRID3, whereas the model for electrification analysis in this study is point based.



The NRECA team also reviewed a series of reports, plans, laws and policies to inform the design assumptions of the electrification plan. These include but are not limited to:

1. 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.
2. Least-Cost Electricity Access Development Project, Project Appraisal Document. World Bank, February 2019
3. Madagascar, Beyond Connections. Energy Access Diagnostic Report based on the Multi-tier Framework. World Bank, July 2022.
4. Mini-grid Market Opportunity Assessment: Madagascar. SE4All Africa Hub & African Development Bank, March 2019.
5. Etude sur l'économie politique de la réforme du secteur de l'énergie, Rapport Final. Dev2E for MEH and AfDB, November 2022.
6. Draft Version Deep Dive Analysis, WP5 Recommendations to include off-grid RE in the NDC update 2019. RLI, 2019.
7. Taking the pulse of Energy Access in Madagascar. Energizing Finance Report Series. 2019.
8. Increased energy access for productive use through small hydropower development in rural areas in Madagascar, Project Implementation Report. UNIDO, June 2022.
9. Evaluation des projets d'électrification rurale décentralisée à Madagascar, Rapport Final. GIZ, July 2020.

10. Etude de capitalisation de 16 projets d'électrification rurale par mini réseaux à Madagascar. Marge, March 2020.

11. Etude de faisabilité pour un Programme d'électrification rurale via mini-réseaux, dans le cadre des appels à projets de l'agence d'électrification rurale. Agence Française de Développement, June 2022.

12. Hydropower Atlas: Final Report, Small Hydro Resource Mapping in Madagascar, The World Bank, April 2017.

13. Plan Emergence Madagascar, 2019 – 2023. Government of Madagascar, 2019.

14. Loi n°2017-021 du 22 novembre 2017 portant réforme du Fonds National de l'Electricité (FNE).

15. Loi n°2017-020 du 10 avril 2018 Portant Code de l'Electricité à Madagascar.

16. Ordonnance n° 75-024 du 17 octobre 1975 portant création de la société Jiro sy Rano Malagasy (JIRAMA) et fixant les statuts de ladite Société.

17. Décret n°2018-261 du 27 mars 2018 fixant le statut et les attributions de l'Office Malgache des Hydrocarbures.

18. Décret n° 2018-383 du 24 avril 2018 Fixant l'organisation, les attributions et le fonctionnement de l'Autorité de Régulation de l'Electricité (ARELEC).

19. Décret n°2018-384 du 24 avril 2018 fixant les missions et attributions, l'Organisation et les modalités de fonctionnement de l'Agence de Développement de l'Electrification Rurale.

20. Décret n°2023-245 du 14 mars 2023 fixant les procédures relatives aux Concessions de Production, de Transport et de Distribution, aux Autorisations de Production et de Distribution et aux Déclarations de Production d'énergie électrique

Data Limitations

Models that forecast project feasibility, costs and financial analysis are limited by the specificity and accuracy of available data. Much of the data for this project were collected from JIRAMA, ADER, donor projects and secondary sources. There was no opportunity to field-validate the data provided for this study. In addition, the geospatial data on JIRAMA's systems and private-sector managed mini-grids are incomplete.[24] For example, data on JIRAMA's distribution network contained various spatial errors, lacked transformers, as well as complete information on conductor sizes per feeder. In the absence of a fully digitized database of the existing distribution network in Madagascar, various assumptions were made to compile a workable dataset – including assigning conductor sizes and types where missing and spatially determining the potential generation plant sites for existing JIRAMA isolated networks, among others.

Additional primary data limitations pertain to two key inputs: the accuracy of the digitized structures and roads and the accuracy of estimates of energy consumption by consumer category. The accuracy of the digitized structure and road data is dependent on the availability and age of satellite imagery. The NRECA team acquired and used the most recent, publicly

[24] JIRAMA officials confirmed that no systematic digitization of its infrastructure has been conducted to date and that the digitization shared for the IEP represents the full extent of available data as of May 2023. MV line digitization seems to have been done point to point indicating that it was likely not field digitized. In addition, there are only a limited number of transformers digitized. Furthermore, digitization of JIRAMA's network outside of the interconnected networks is ad hoc; some of the larger towns have digitized networks but many of the smaller JIRAMA isolated sites are only represented by a point.

available imagery to digitize both housing structures and roads. The ability to digitize housing structures is extremely useful as a means of projecting the geographic concentration of load over large spatial areas. However, it is not possible to determine occupancy or activity type for each structure. Rather, digitized structures are used to approximate load density by calculating the number of buildings in each area and assuming homogeneous load characteristics over large, digitized building clusters. The drawback of this method is that it may result in under-valuing small commercial loads that are undoubtedly present in some housing clusters, but it does allow the geospatial allocation of load to high-density areas and the distribution of load according to housing cluster patterns. While there are undoubtedly locations where the load is undervalued, in general this approach provides much higher resolution than estimating load in the absence of housing structure data. Additional data collection and analysis may be required to point loads associated with agricultural enterprises, irrigation and small industrial activities, among others.

However, although data limitations exist, this fact alone does not impose a significant risk to the IEP given that it is a planning tool, used for building a policy and investment case at the macro level. More accurate data will be needed during implementation and the next phases of electrification implementation. To support subsequent implementation phases, it is strongly recommended to:

- Conduct a full digitization of JIRAMA's grid infrastructure and the distribution systems of all operating mini- and isolated-grid sites to construct a complete database that can support detailed project planning as well as operations
- Conduct field data collection to accurately locate and size loads associated with agricultural enterprises irrigation, small industrial activities, among others.

Energy Expenditure Surveys

Methodology

The energy expenditure survey was conducted on a sampled basis in selected mini-grid project service areas in northern, central and southern zones of Madagascar. The survey was designed to employ random sampling to identify specific enumeration targets through which enumeration team members were guided to administer the survey questionnaire to survey participants. The questionnaire was designed to collect data regarding sources of fuels, energy services and expenditure by type of service including lighting, mobile phone charging, entertainment, productive use and cooking. Responses were recorded on GPS-enabled tablet computers. A team of enumerators was hired and trained to conduct the survey at the randomly selected households and businesses for each of the three survey areas. The enumerators were hired by AIDES (a Malagasy consulting and survey firm) and trained by the NRECA survey specialist. The survey forms were developed and programmed into a platform called Open Data Kit (ODK), which allows for multiple question types and languages. The surveys were developed in French, while enumerators communicated in Malagasy as required.

The sampling methodology was a two-stage purposeful sample. The selection process began by coordinating with ADER to review the population and distribution of all private mini-grid sites operating in Madagascar. The mini-grids were divided into southern, central and northern zones of Madagascar to ensure geographic diversity in the survey process. In the next step, the mini-grids were divided by technology – solar PV mini-grids and hydroelectric mini-grids; a decision was reached to ensure that the sampling frame would include surveys for both generation technologies. The population of mini-grids was also classified by service provider, and in addition to ensuring that the sample included representation by both solar and hydro generation technologies, SEforALL and NRECA also determined that the survey sample should include representation from the two largest mini-grid providers; WeLight and ANKA. Lastly, selection of the survey areas required that the survey team could complete the survey within a restricted schedule, so the final site selection discarded sites in more remote and less accessible areas of Madagascar. Using these selection criteria, NRECA proposed a final analysis of sites and selection of survey areas to SEforALL and ADER and a final selection was completed.

Once the sites had been selected, a second stage of sampling was undertaken for each survey area to create the final sampling frame for four respondent types – electrified/unelectrified residential respondents and electrified/unelectrified commercial and institutional respondents. NRECA proposed that each sample contain approximately 350 households and 100 non-households (commercial and institutional) per sampling frame.25 This sample size was split evenly between the electrified mini-grid area and the non-electrified area to proportionally sample respondents. That is, the survey sample included 175 electrified area and 175 non-electrified area residential survey respondents for each sampling frame, as well as 50 electrified area and 50 non-electrified area non-household survey respondents. A sample size calculator26 was used to define the sample size target of up to 350 household surveys for each sampling frame. This was an estimate based on a maximum household population of 4,000 per site, with a 5 percent margin of error and 95 percent confidence level.

To randomly select survey respondents, the GIS database of structures was used to randomly sample structure points to complete the required sample size plus a margin of additional survey sites to account for unoccupied structures and non-available respondents. In addition to the randomized structures, the survey team also used purposeful sampling to sample unelectrified non-residential structures. In each mini-grid service area sampled, the approach was to create a simple random sample that targets respondents with electricity from the mini-grid and those that are not connected.

In each mini-grid service area sampled, the objective was to survey a combination of mini-grid consumers and unelectrified households and small business owners. Table 3 illustrates the balance of mini-grid consumer and unelectrified households that were surveyed in each of the three zones that the energy expenditure survey was undertaken.

Table 3. Samples completed per sample frame

Zone	Mini-grid	Electrified HHs	Unelectrified HHs	Total Households	Electrified Businesses and PF	Unelectrified Businesses and PF	Total Bus & PF

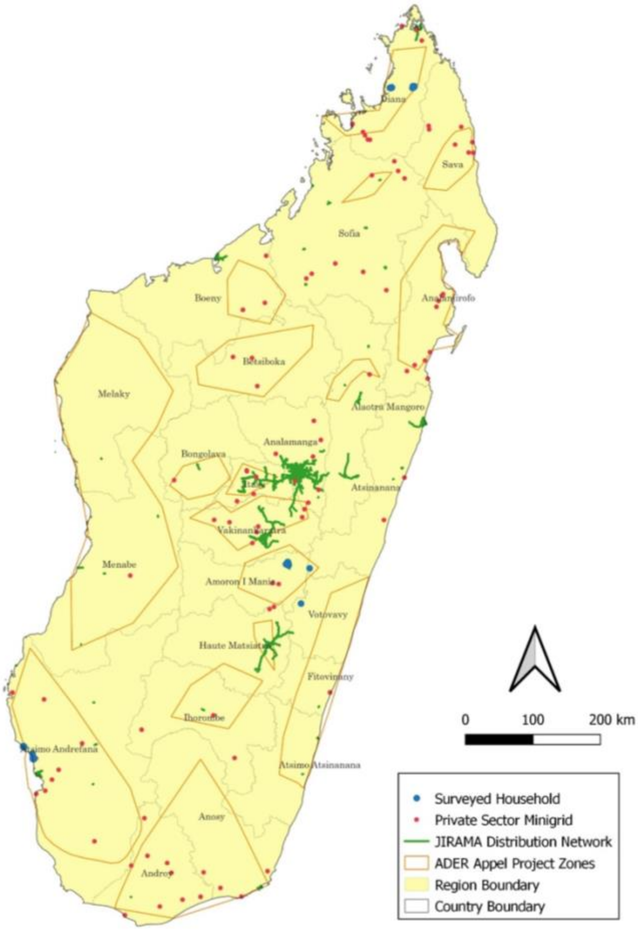
[25] The non-household sample was estimated based on NRECA experience conducting similar surveys in other geographies and the estimated household population. The non-household sample was then adjusted according to the survey supervisor's evaluation of the total population of public facilities and businesses at each site.

[26] See - https://www.calculator.net/sample-size-calculator.html

North	WeLight	180	180	360	55	55	110
Central	HEIR	180	180	360	55	57	112
South	ANKA	176	180	356	55	54	109
Total		**536**	**540**	**1076**	**165**	**166**	**331**

While the results of the energy expenditure surveys provided valuable data on energy usage and spending patterns, due to limitations of funding and time, the survey sample was limited to three zones and five sites. Projecting the results to all regions in Madagascar should be undertaken with caution.

Figure 8. Location of energy expenditure surveys, July 2023



Energy Expenditure Results

Energy expenditure data have been historically used to evaluate electricity consumption, to evaluate demand growth and to project connection rates for electrification projects. Results of energy expenditure surveys illustrate actual levels of energy use by residential, commercial and public facilities. Energy expenditure results are sometimes referred to as “revealed willingness to pay.” Survey results are used to evaluate consumption levels by decile of the served population, and thereby to project consumption of energy for the population of consumers. This section of the report presents the energy expenditure results for each surveyed zone.

Approximately 80 to 90 percent of electrified households surveyed reported a direct connection to the mini-grid service provider, while approximately 10 percent of electrified households were connected to a neighbouring household. A relatively small percentage of unelectrified households in the electrified (mini-grid) service areas relied on standalone solar solutions for their electricity needs. In sample areas outside the reach of mini-grid service providers, approximately 35 to 45 percent of households reported using standalone solar solutions for their electricity needs, in addition to rechargeable batteries (mainly for mobile phones) and AA batteries. In the southern zone unelectrified households reported a significant kerosene usage at 38 percent of sampled unelectrified households.

Table 4 and Table 5 summarize the monthly energy expenditure by percentage of respondents for residential, commercial and public facilities sampled in all three zones. The high expenditure category corresponds to the top 20 percent of all residential and commercial consumers, while the medium category corresponds to 20 to 50 percent of the residential and commercial consumer population. The low category corresponds to the bottom 50 percent of residential and commercial consumers. Note the significant difference between electrified and unelectrified commercial and public facilities surveyed.

It is also worth noting that tariffs charged by mini-grid service providers vary significantly. The mini-grid service provider Fandriana in the central zone charges the lowest average tariff (USD 0.14 per kWh). Mini-grids in the northern zone reported the highest tariffs that are charged based on a pricing bundle for a fixed quantity of energy over a set duration – similar in nature to mobile phone data bundles. The bundled prices provide single-phase consumers with between 0.13 kWh for a single day and 18 kWh over a 30-day period at prices that vary between MGA 800 to 65,0000. For the 30-day bundles, this equates to a tariff of approximately USD 0.83 per kWh. This in part likely explains why expenditure for electrified customers is higher in the northern zone than other zones.

Table 4. Monthly residential energy expenditure by zone for northern, central and southern zones

Residential		Electrified USD/Month	Unelectrified USD/Month	Electrified USD/Month	Unelectrified USD/Month	Electrified USD/Month	Unelectrified USD/Month
Zone:		Northern		Central		Southern	
10%	High	$21.84	$5.41	$ 7.37	$5.35	$16.34	$5.87
20%		$14.67	$3.53	$ 4.74	$3.98	$9.76	$3.80
35%	Medium	$9.55	$2.61	$ 3.80	$2.88	$6.02	$2.70
50%		$7.25	$2.10	$ 3.46	$2.15	$4.83	$1.82
75%	Low	$6.91	$1.00	$ 2.43	$1.15	$2.95	$1.07
90%		$5.52	$0.72	$ 1.25	$0.70	$1.97	$0.38

Table 5. Monthly commercial energy expenditure by zone for northern, central and southern zones

Commercial and Public Facilities		Electrified USD/Month	Unelectrified USD/Month	Electrified USD/Month	Unelectrified USD/Month	Electrified USD/Month	Unelectrified USD/Month
Zone:		Northern		Central		Southern	
10%	High	$85.49	$147.25	$40.28	$3.30	$43.40	$13.46
20%		$51.79	$10.59	$19.73	$2.65	$27.62	$6.91
35%	Medium	$23.02	$3.89	$11.51	$0.86	$18.15	$3.73
50%		$15.33	$2.50	$8.38	$0.53	$10.11	$2.77
75%	Low	$7.14	$1.27	$4.14	$0.01	$4.93	$1.04
90%		$5.18	$0.30	$2.49	$0.01	$2.58	$0.24

The results of energy expenditure, presented in Tables 4 and 5, were used to corroborate the energy consumption levels with which demand was evaluated for on-grid and off-grid projects within the electrification results described in this report. These results illustrate differences in consumption and expenditure patterns between the three regions and demonstrate a substantial latent demand for energy services for commercial and public facilities. As stated previously, the results provide a useful assessment of energy expenditure trends in Madagascar that can be combined with other sources of information from ADER, private operators or other donor-funded programmes to provide robust estimations of household, commercial and public institutions' demand and potential electricity consumption. However, due to the timeline between the completion of the energy expenditure surveys and the electricity analysis, the results of the surveys were not available to feed directly into the electrification model, nonetheless the two corroborate the energy consumption values chosen for residential commercial/public facility loads. These estimated are provided in the design assumptions section below.

Geospatial Modelling Framework

This section describes the geospatial modelling framework used to develop the least-cost electrification options analysis, building on the presentation of the input and output datasets presented in the inception report. Additional methodological information and detailed parameters are available in the annexes of this report.

Data input to the geospatial platform

Electrification expansion planning requires multiple sources of data with which the geospatial platform can be used to identify and evaluate electrification project options. Project identification uses geographic characteristics, evaluation of housing patterns, energy expenditure results and other parametric data to evaluate densification, grid expansion and off-grid electrification solutions. When these analyses are completed, they can be aggregated, presented and visualized in the platform. To begin the process of electrification expansion analysis, the following data are required:

Table 6. Data input to the geospatial platform

Type of data	Attributes	Date Provided	Source	Use in modelling
Administrative/Political boundaries	These include regional, district, commune and fokontany boundaries	June 2023	HDX for districts, communes, and fokontany, and UN OCHA for regions	Provides administrative boundary extents, used to aggregate project and electricity access impacts by administrative boundary
Road network	Primary, secondary and tertiary roads	May 2023	OSM	Used for least-cost routing path for MV and LV feeders
Population data	Population data derived from the most recent census mainly the "Troisième recensement général de la population et de l'habitation", or RGPH-3	RGPH was completed in 2018, accessed in May 2023	INSTAT	Provides estimates of population and households, as well as inputs to growth rates
Network data	Transmission grid and primary substation locations, MV line alignments, locations of isolated distribution networks, etc.	May 2023	ADER and JIRAMA	Required inputs for definition of electrified areas for densification analysis, as well as routing of new grid extension projects
Electricity consumption data	Electricity consumption data were derived from the existing 2022 JIRAMA commercial database, MTF survey, ADER demand estimation parameters exported from GEOSIM and other donor-supported studies.	May 2023	JIRAMA, World Bank ESMAP, ADER, AFD, among others	Required input to develop load assumptions for the clustering of structures into servable areas
Structures	Digitized points of structures in Madagascar based on recent satellite imagery	April & May 2023	Google Open Buildings	Required input, used as primary source of potential connection locations
Terrain or landbase features	Rivers, lakes, forests, national parks, etc.	May & June 2023	ADER and World Bank Small Hydro Atlas	Required input, used to limit or filter on-grid and off-grid line extension so as not to cross major terrain feature or protected areas
Material and construction costs	Unit costs estimates for conductors by voltage, transformers, service connections and others	May 2023	NRECA developed cost database, various sources, 2023	Required input to produce cost estimates for all electrification infrastructure and projects

The input data layers and attributes include a combination of spatial and non-spatial data. One of the key spatial inputs is digital housing structures as presented in the section above. In addition to these geographic data, the team also evaluated material costs related to construction and maintenance, operating costs, energy consumption patterns and tariffs. Indicative cost data were provided by JIRAMA however they were from 2010, and do not reflect recent cost trends, NRECA elected to use regional costs, primarily from Mozambique, and thereafter integrated the data into the geospatial framework in input tables. These estimates were also validated with the Energy Planning Unit, which includes ADER, JIRAMA, MEH and ORE. nput tables, which will be delivered to stakeholders as a part of the IEP, can be modified as needed to evaluate project costs, revenues and characteristics as projects are financed over time. Further details on these assumptions are provided in the section below.

Electrification analysis

The geospatial model was designed to evaluate grid and off-grid expansion using housing structure data in conjunction with distribution system attributes, estimates of monthly consumption, and construction cost estimates for grid and off-grid electrification solutions. The data and parametric values are stored in the geospatial database that includes data from the JIRAMA transmission and distribution network. The database will be delivered to stakeholders as part of the IEP, and includes housing structure data, road data, population data and other geospatial and demographic attributes that are used to evaluate electrification, medical cold chain, agricultural cold chain and clean cooking analysis. The outputs and main data layers from the geospatial database will also be presented on an interactive data visualization platform, discussed elsewhere in the report.

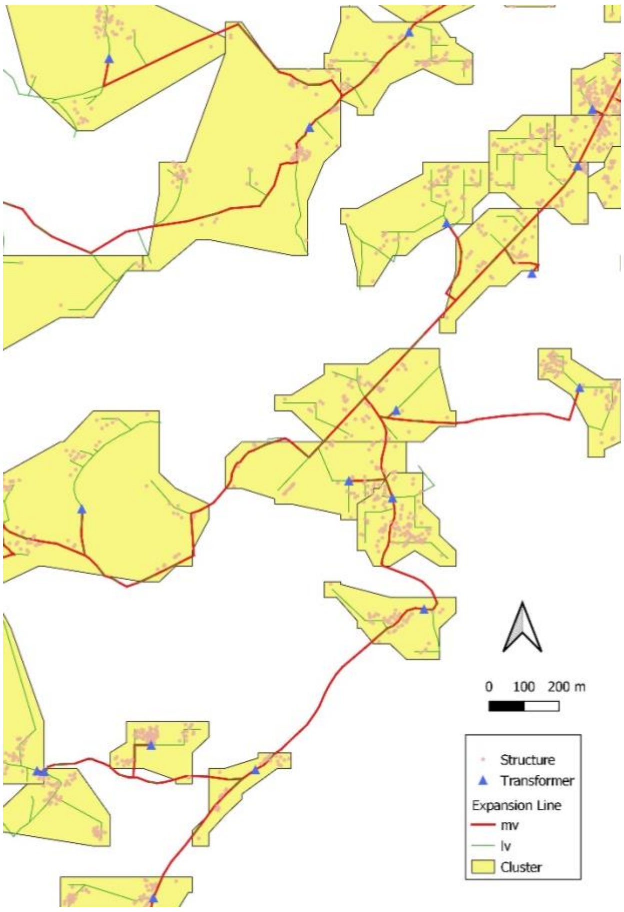
The electrification-specific analysis conducted in the geospatial database includes evaluation of grid densification, grid expansion and off-grid electrification solutions. These analyses were performed using a clustering algorithm to aggregate demand and a routing algorithm to optimize low voltage (LV) and medium voltage (MV) line alignments. After evaluating the magnitude and geolocation of demand, and defining optimal line routing, a third step to evaluate technology cost was applied. The order of these analyses/processes was as follows:

1. The clustering algorithm was used in combination with the digitized structure data and energy expenditure and consumption data to aggregate demand – at the centroid of each cluster of digitized households.
2. The routing algorithm was used in two stages – first to route LV networks for each cluster and then to interconnect transformers (for each cluster) in conjunction with the road network data to define MV line alignments.
3. Finally, after transformer locations (and sizes) and LV/MV network alignments had been defined, an evaluation of distribution cost was evaluated using data from the clustering and routing results to determine MV and LV feeder costs, transformer costs and the cost-of-service connections and meters as a function of served households.

The clustering and routing algorithms employ parametric data-stored data tables. These values are shown in Annex 1. After completing the clustering, routing and cost analyses, results were organized in three categories; housing structures that are within 600 meters of MV distribution infrastructure were evaluated for grid densification;[27] grid expansion projects that comply with voltage drop limits and do not exceed a pre-determined maximum cost per consumer served; and all other areas that are thereafter evaluated for off-grid service – which included three main categories: MV metro and mini-grids, LV mini-grids, and standalone solar solutions.

[27] 600 meters is a typical radial distance that can be served by a distribution transformer. Beyond this limit, the line will experience voltage and power quality issues.

Figure 9. Illustration of clustering and routing analysis for Madagascar



Electrification modalities

Analysis of electrification expansion options is a central task of the IEP. Electrification expansion planning is performed by identifying expansion needs and then evaluating least-cost solutions to meet household, commercial and public facility needs in urban, peri-urban and rural communities. Expansion of service can be achieved by connecting households that are close to existing JIRAMA service, a process referred to as densification; by extending MV service to unelectrified communities and housing clusters, a process referred to as grid expansion; and, by serving unelectrified communities and housing clusters with mini-grids or standalone solar systems, a process referred to as off-grid electrification expansion. In each electrification expansion modality, the objective is to provide the most cost-effective solution that provides the level and type of service needed at the lowest cost, while meeting consumer needs.

Off-grid electrification solutions were evaluated with grid densification and expansion solutions to determine where mini-grid service could be used at a lower cost than grid expansion. As a starting point, mini-grids were evaluated in all areas where grid expansion costs equal or exceed USD 1,250 per served consumer.[28] Both grid expansion and mini-grid options were evaluated

[28] The value of USD 1,250/consumer was chosen relative to the likely cost of mini-grid expansion. See Agenbroad, Carlin, Ernst, and Doig, Mini-Grids in the Money, Rocky Mountain Institute, 2018. https://rmi.org/wp-content/uploads/2018/12/rmi-seeds-minigrid-report.pdf.

based on the levelized cost of energy (LCOE). That is, the solution with the lower LCOE is selected as the preferred electrification solution. Solar standalone options were evaluated as a function of the limits of grid expansion and mini-grid viability.

The sequence of analysis in the geospatial analysis that was employed is as follows, please also see the routine rules section below that provide further details and justifications for the parameters selected:

Evaluate grid densification potential. Densification analysis was performed by comparing the number of housing structures within a fixed radius of each distribution transformer with the number of JIRAMA consumers served by that same transformer. Given that JIRAMA has not mapped consumers by transformer, densification analysis required analyzing the potential consumer base in conjunction with digitized housing structures using a 600-meter radius to capture and evaluate the number of structures for each JIRAMA system (interconnected or isolated). Comparing the total number of structures against the estimated number of JIRAMA consumers, densification potential was evaluated. Densification costs include the cost of a service connection (up to 50 meters of triplex conductor, a weatherhead and a single-phase revenue meter) with less than 10 meters of LV line and an allowance for 1/100th of additional transformer capacity related to each new consumer connection. Densification costs were aggregated by JIRAMA service centre; additional transformer capacity was evaluated to define the number of new transformers required. The estimated cost of densification is USD 375 per connection.

Evaluate grid expansion potential. Grid expansion projects were identified by clustering structures using a cluster radius of 600 meters to determine where sufficient load exists to serve these clusters with JIRAMA service. A routing algorithm was then employed with the road network data layer to define the MV line alignments needed to interconnect clustered households and associated transformers. Demand for all transformers was evaluated using an estimated consumption of 61 kWh/month/consumer for year 10 of the project – which is a weighted average value that takes into account estimated consumption values and consumer-mix projections for residential, commercial and public facility consumption. This figure was proposed by NRECA to SEforALL based upon JIRAMA commercial data and has been used to evaluate grid expansion for all areas within a 15-kilometer radius of existing JIRAMA distribution networks. For housing structures beyond 15 kilometers of JIRAMA service, which is an approximation for the likely maximum grid extension possible for existing 20 kV networks without the ability to run a load flow model, 26 kWh/month consumption was used corresponding to expected consumption in year 10. Transformer capacities and costs were then evaluated to meet the needs of all housing clusters in grid expansion areas. MV line alignments were defined taking into consideration that voltage drop should not exceed 10 percent for any line extension, and design of MV alignments follow roads as their least-cost path.

Mini-grid analysis. For population clusters that cannot be economically served by grid expansion, mini-grid service was evaluated. Mini-grid analysis for Madagascar considered two design approaches, one for smaller, single-community mini-grids and a second for larger, multi-community mini-grids, also referred to as MV mini-grids for the purposes of the IEP. For single community mini-grids using solar PV hybrid generation systems, these systems were designed to use LV distribution systems and dimensioned to provide service to a minimum of 100 structures in areas where multiple communities could not be readily interconnected due to high connection costs. Single-community mini-grids were designed to use LV distribution networks, to economize on capital costs and assume periodic maintenance by a regional O&M team. Larger, multi-community mini-grids were designed to use MV networks to serve multiple communities and larger housing clusters. These larger, MV mini-grids are further categorized as either grid-edge MV mini-grids or isolated MV mini-grids, depending on their spatial proximity to existing JIRAMA interconnected networks. MV isolated grids are also sometimes referred to as "metro-grids" due to larger power generation capacity and associated larger communities that are served. The terminology used for purposes of the IEP is isolated MV mini-grids. Mini-grid characteristics were evaluated using a simplified mini-grid design algorithm[29] to evaluate generation, storage and control characteristics that were later verified and updated in HOMER Energy.

Solar standalone solutions. For areas beyond reach of grid expansion and where mini-grids are not viable, solar standalone solutions can be used to provide entry-level electrification service.

Affordability

Understanding consumer affordability is extremely important in electrification expansion analysis. Consumer affordability is most effectively measured by evaluating the results of energy expenditure surveys for residential and small commercial enterprises. The goal of energy expenditure surveys is to understand expenditure patterns to project likely consumption of electricity when commercial service is offered through grid or off-grid service in the future.

Several sources were used to estimate affordability data for the IEP, including the JIRAMA 2022 commercial data; the World Bank/ESMAP Multi-Tier Framework (MTF) Energy Access Household Energy Survey completed in 2022; ADER electricity consumption and demand projections, which are understood to be based on the results of the GLCEP; and a French Development Agency (AFD) report on AP4 mini-grids. The most important source of data, however, was the previously described residential and commercial energy expenditure surveys that recorded expenditure for electrified and unelectrified communities in three zones of Madagascar. The results of the survey were used to affirm the projected electricity consumption for on-grid and off-grid service in the geospatial model.

While other sources, such as the MTF study, provide estimates of energy consumption, the MTF results project a much higher level of consumption particularly in urban areas; MTF projections indicate that rural households spend MGA 427,929 (USD 93) and urban households approximately MGA 487,364 (USD 106) per month. Overall, the national average household energy expenditure as measured by the MTF is MGA 466,282 (USD 101) per month. These expenditure levels are much higher than survey data indicate. That is, the highest decile of the energy expenditure survey from the northern zone reports an expenditure level of USD 22 per month, nearly five times lower than rural household MTF values. Energy expenditure in the

[29] The simplified MG design algorithm allows for an accurate dimensioning of a large set of mini-grids, by modelling several archetype mini-grids in HOMER, then applying a series of ratios that are outputs of the HOMER models to model the full project list of mini-grids proposed in the planning exercise.

highest-consuming decile for central and southern zones reported expenditure levels of USD 7.37 and USD 16.34 respectively. Unelectrified residential respondents report significantly lower levels of expenditure; median expenditure levels reported USD 2.10, USD 2.15 and USD 1.82 in the northern, central and southern zones, respectively.

Affordability is directly related to expected electricity consumption; further details on the estimates of electricity consumption are presented below.

Design Assumptions

Routing rules

The Madagascar IEP – Electrification Routing Rules report included in Annex A1 presents the methodology that was used to guide geospatial electrification modelling for the Madagascar IEP in detail. The modelling process used to characterize demand, evaluate transformer and conductor requirements and to route MV and LV networks is fundamentally guided by the routing rules presented in Annex A1. This section describes the clustering and routing methods that use the routing rules to execute the model.

Parameters for Clustering

The clustering algorithm aggregates housing structures into clusters to determine where transformers or mini-grids can be installed to provide electrification solutions to these aggregated as the basis for electrification analysis. The primary parameters for establishing the electrification clusters are defined below.

Clustering Radius

Clustering is performed by using digitized housing structure locations to aggregate housing structures in clusters defined by 600-meter radii to determine where transformers can be located to serve unelectrified communities. Prior to running the clustering algorithm, the first step is to evaluate the number of digitized structures per household. This is done by comparing the total number of digitized structures to the number of households reported by the most recent census and projecting the number of households by the population growth rate as published by the World Bank. For Madagascar, the ratio of households to digitized housing structures is 1.04.

This ratio is used to determine the number of consumers represented by digitized structures in the geodatabase. This ratio is often less than one in rural areas, where individual households may use multiple structures, while the ratio is most often greater than one in urban areas where apartment buildings are more widely used. For this project, the geospatial team evaluated the 2018 population and household data by district and region and projected these values from 2018 to 2023 using a population growth rate of 2.4 percent. The projections were then compared with the results of the housing structure digitization for each region that resulted in a national average of 1.04 household per structure.

Demand Formula

Peak demand can be evaluated by approximating the coincidence factor for each category of loads and consumers and using the load distribution and coincidence assumptions, then a load shape can be approximated for a typical day. Alternatively, the Rural Utilities Services, a United States government agency, developed a data base of consumption data from 1,000 rural utilities serving more than 10 million consumers that was correlated with demand data. The energy consumption and demand data were then correlated in a regression analysis using two primary regression variables – the number of consumers and average monthly energy consumption in kWh. This demand formulation was documented in the US Rural Electrification Administration in REA 45-2 Bulletin.[30] The regression formula is comprised of two factors, the Consumer Factor (Factor "A") and the Electricity Consumption Factor (Factor "B"). Factor "A" reflects the diversity that results from increasing the number of consumers, and Factor "B" reflects the change in load factor that results from an increase in the energy use per consumer. The formula is as follows:

D = (Factor A) * (Factor B)
Factor A = C*(1-0.4*C+0.4*(C^2+40)^0.5)
Factor B = 0.005925*(kWh/month/consumer)^0.885

Where:

D = Demand (kW)
C = number of consumers

In addition, the kWh/month/consumer varied according to the following:

- The weighted average consumption **26 kWh/month/consumer** for year 10 of the project for structures beyond 15 kilometers from known JIRAMA distribution grids/systems

This weighted average consumption value is derived from three sources, as shown in Table 7. Data from ADER provided a rural residential monthly electrification consumption estimate of 19 kWh/customer-month for a 'medium' household, and 4 kWh/customer-month for a 'low' household and 60 kWh/customer-month for a 'high' household, while the AFD study of mini-grids in AP zone 4 indicated a kWh/month for all customers of between 9 to 20 kWh/customer-month. A value of 19 kWh/customer-month was taken for this assumption. Data from JIRAMA's 2022 customer database for rural consumers were used to estimate commercial and institutional consumption. Consumer mix estimates are derived from the same three sources.

Table 7. Weighted average consumption for structures beyond 15 kilometers from known JIRAMA distribution grids/systems

Consumption and annual growth	Consumer Mix (%)	Unit	Year 1	Growth yr 2-5	Growth yr 6-10
Residential (Source: ADER & AFD)	99%	kWh/Cust-month	19	2.0%	2.0%
Commercial & Institutional (Source: JIRAMA)	1%	kWh/Cust-month	240	3.5%	2.0%
			Year 1	Year 5	Year 10
Weighted average for clustering		kWh/Cust-month	21	23	**26**

[30] "USDA Rural Development's Electric Programs - Bulletins." United States Department of Agriculture - Home. 26 Feb. 2009 http://www.usda.gov/r us/electric/bulletins.htm.

The weighted average consumption is **61 kWh/month/consumer** for year ten of the project for structures within 15 kilometers from known JIRAMA distribution grids/systems (see Annex A1 and A2 for weighted average consumption assumptions).

This weighted average consumption value is derived from the same three sources as presented above and as shown in Table 8. The residential kWh/customer-month has been increased in line with the ADER 'high' household value, higher AFD study residential consumption rate and the JIRAMA rural residential average consumption rate of 60 kWh/customer-month.

Table 8. Weighted average consumption for structures within 15 kilometers from known JIRAMA distribution grids/systems

Consumption and annual growth	Consumer Mix (%)	Unit	Year 1	Growth yr 2-5	Growth yr 6-10
Residential (Source: ADER & AFD)	95%	kWh/Cust-month	40	2.0%	2.0%
Commercial & Institutional (JIRAMA)	4.996%	kWh/Cust-month	240	3.5%	2.0%
Medium Industrial (JIRAMA)	0.004%	kWh/Cust-month	11900	5.0%	2.0%
			Year 1	**Year 5**	**Year 10**
Weighted average for clustering		kWh/Cust-month	50	55	**61**

Cluster size: urban and peri-urban

For structures within 15 km of JIRAMA network service, the minimum number of rooftops that can comprise a single cluster is 10 structures. Ten structures can be served by a 15 kVA transformer; this will result in a load of 35 percent in year 1 and will not exceed 80 percent of transformer capacity in year 10. Clusters with fewer than 10 rooftops are designated as standalone solar systems. Further details are available in Annex A.

Cluster size: rural

Grid expansion: For structures beyond 15 km of JIRAMA grids, the minimum number of rooftops to form a cluster is 40. This will load a 15 kVA transformer to 50 percent of its rating at year 10. Clusters with fewer than 40 rooftops should be redesigned or assigned to standalone solar systems. Mini-grids with total clusters within a 1000 m radius with fewer than 100 rooftops should be redesigned or assigned to standalone solar systems. Further details are available in Annex A.

Transformer assignment and sizing

Transformers serving the clusters should be sized so that the average load does not exceed 50 percent of transformer capacity at year 10, calculated using the methodology described above. This provides flexibility in the clean cooking plan for higher e-cooking assumptions without redesigning the distribution system. The smallest transformer size allowed is a 15 kVA single-phase transformer. Smaller 15 and 25 kVA transformers will be single phase given the lower cost of smaller, single-phase transformers. All transformers 50 kVA and larger will be three phase. Further details are available in Annex A.

Demand and transformer sizing

Demand tables defined to guide clustering and dimensioning transformers are shown in Annex A1 and A2, while A3 presents cost estimates for distribution materials and Annexes A4 and A5 present load assumptions.

Parameters Contributing to LV & MV Routing

Once housing clusters are defined in the clustering algorithm, a routing algorithm interconnects transformers to MV feeders and laterals and connects LV feeders to consumers. LV routing is performed first to route LV feeders to interconnect all structures while the same routing algorithm will be used thereafter to interconnect transformers to MV feeders and the feeders to substations. The MV feeders and taps are always built along roadways to facilitate operation and maintenance procedures. LV circuits follow roadways when possible but may be built along pathways that are not served by roads when necessary. Both the MV and LV routing models are also used to evaluate the cost of feeders, laterals, transformers and other distribution line element costs.

Medium voltage (MV) routing

JIRAMA uses 20kV as the MV distribution standard throughout its distribution system. The 20kV network uses a three-wire ungrounded configuration where the system is neutral grounded at substation. As a cost-saving measure, grid expansion design used single-phase 15kVA and 25kVA transformers, while all transformers 50kVA and larger are three-phase transformers. All smaller transformers up to 50 kVA will be mounted on single poles, while larger transformers over 50kVA will be mounted on two pole H-frame structures.

Parameters for determining electrification modality in off-grid clusters

After completing LV and MV routing and the related densification and grid expansion analysis, all other structures that were excluded from grid densification and expansion are evaluated for mini-grids and solar standalone off-grid options. The following section describes how off-grid electrification expansion was evaluated in the electrification modelling process.

Distinguishing between grid expansion and off-grid clusters

Digitized housing clusters were initially evaluated for grid expansion service by evaluating transformer capacity needed to adequately serve each housing cluster and then interconnecting clusters and evaluating the infrastructure cost of the grid expansion projects. The projects whose costs are less than USD 1,250 per consumer are included in the grid expansion database. For projects whose cost is greater than USD 1,250 per consumer, clusters were reconfigured into mini-grids and evaluated on a levelized-cost of energy (LCOE) basis to determine which option produces the lower cost. If the LCOE analysis yields a more attractive result for mini-grids, the projects will be considered in the mini-grid portfolio.

Distinguishing between mini-grid and standalone solar options

Off-grid clusters will be classified as metro-grids, mini-grids and standalone solar systems. The primary distinguishing factor will be the total electricity demand in each cluster, which can be approximated by the number of connections in the cluster. Clusters of fewer than 100 connections within a 1,000-meter radius will be classified as solar standalone solutions. Clusters of more than 100 connections within a 1,000 m radius will be evaluated for LV mini-grids.

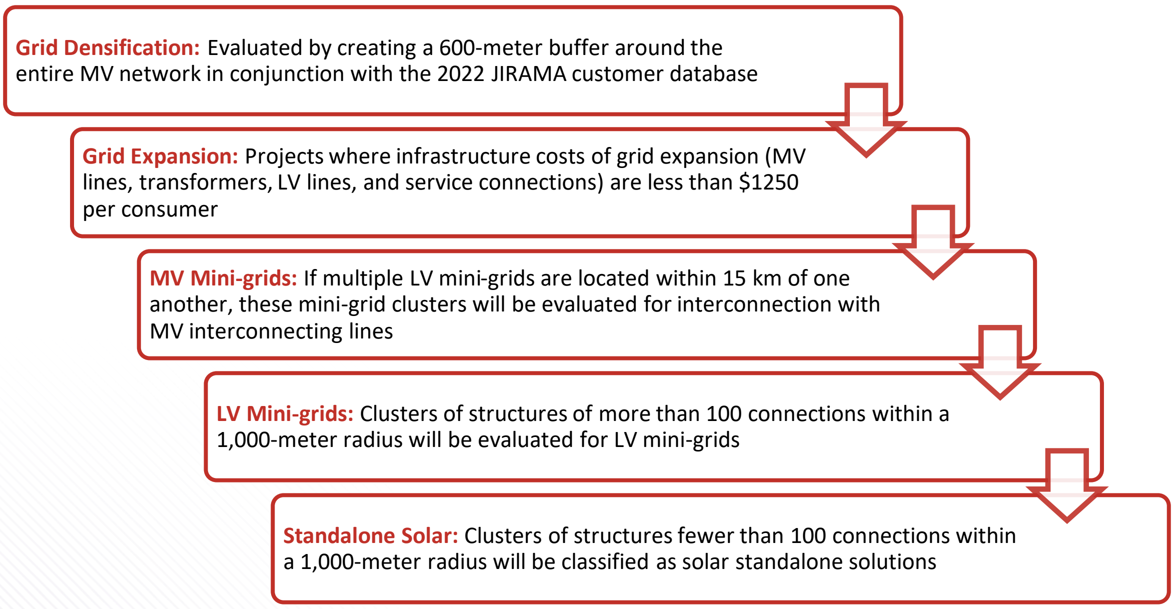
For LV mini-grids, the LV routing algorithm will evaluate the incremental costs of connection. If any of the structures within the proposed MV or LV mini-grid cluster require more than USD 2,000 per connection, then these structures will be excluded from the mini-grid and assigned to solar standalone service.

Distinguishing between LV mini-grids and MV mini-grids

If multiple LV mini-grids are located within 15 km of one another, these mini-grid clusters will be evaluated for interconnection with MV interconnecting lines. While use of MV interconnectors will incur significant cost, the added cost may be offset by improved revenues over the interconnected isolated grid via a larger and centralized generation plant. That is, the LV mini-grid generation would be replaced with transformers and a central generation plant will be used to provide power supply to all interconnected housing clusters. The power generation system will consist of a solar-battery-diesel hybrid generation plant dimensioned to achieve a renewable fraction that exceeds 75 percent.

Figure 10 illustrates the decisionmaking process described above to distinguish between grid expansion and off-grid (mini-grids and standalone solar options).

Figure 10. Parameters for determining electrification modality



Methodology for LCOE calculation

After determining which communities will be served by smaller LV and larger MV mini-grids, all mini-grids were organized by number of consumers, evaluated demand and generation capacity. While there is a large number of LV mini-grids, the variation in size is relatively small. Most LV mini-grids are between 100 and 200 structures – the median size is 126 structures, and 75 percent of all LV mini-grids have less than 160 structures. With this in mind, HOMER models were run for three LV mini-grid sizes: (1) the median of the LV mini-grid population (126 structures); (2) the size equivalent to 75 percent of all mini-grids (160 structures); and (3) the largest mini-grid (437 structures). HOMER models were evaluated for solar-diesel hybrids with optimized generation and for a 100 percent renewable fraction.

The LCOE was evaluated for mini-grid size (126, 160 and 437) to determine the capacity of solar array (kWp), solar inverter (kW), battery storage (kWh), and battery inverter (kW) as a function of peak demand. The characteristics of the mini-grids for which HOMER models are evaluated were then used to project capital costs and other key characteristics for all mini-grids in the group of IEP mini-grids.

Capital costs for the major mini-grid components such as solar PV arrays, BESS, inverters and other costs were derived from a review of literature for mini-grids tailored to the Madagascar market. For LV mini-grids with fewer than 300 connections, the CAPEX assumptions reflect smaller capacity equipment and higher unit costs. For LV mini-grids exceeding 300 connections, the CAPEX assumptions reflect larger capacity equipment purchased in bulk for larger mini-grid portfolios.

Capital cost analyses for larger MV mini-grids were evaluated using cost estimates for utility-scale solar PV systems. The MV routing and transformer assumptions are comparable to the costs used in the grid expansion analysis. Once these analyses were completed, the engineering team evaluated LCOE for all mini-grids. The LCOE for larger mini-grids was then compared with grid expansion service options.

JIRAMA isolated grids

Densification potential for JIRAMA isolated grids was performed using a 600-meter buffer, after which housing clusters within 15 kilometers of these networks were evaluated for grid expansion service. Given the uncertainty of the condition of JIRAMA isolated MV networks, the grid expansion analysis includes an allowance for rehabilitation of the 20 kV systems to improve the quality of service.

Mini-grid technical assumptions

A detailed analysis was performed to evaluate distribution network characteristics, solar generation capacity (in kWp), battery capacity (in kWh), customer connections and other relevant parameters to define design characteristics of each mini-grid. Mini-grids were evaluated for 24-hour power supply, consistent with international best practice. The design targets were programmed into the geospatial platform in the geospatial model, after performing the HOMER modelling exercise described above.

For both MV and LV mini-grids, the overall mini-grid population was characterized according to maximum, minimum, median and upper/lower quartiles of customer connections and associated peak demand. Three representative communities were selected from the mini-grid populations to characterize demand and mini-grid dimensioning. These representative samples were selected to achieve diversity both in grid size and geographical location within Madagascar and to identify diversity in solar global horizontal irradiance (GHI) within the dataset. Each of the representative mini-grids was analyzed in detail in HOMER to determine optimal solar and battery sizing and key mini-grid dimensioning ratios between peak demand and optimal asset sized. The dimensioning ratios were evaluated across the different customer densities and GHI characteristics to derive key dimensioning ratios that could be extrapolated to the mini-grid population across all of Madagascar. For the LV mini-grids, solar and battery systems were sized based on the key ratios interpolated from HOMER sizing results of different mini-grid sizes and GHI input values, then extrapolated to the rest of the country. For MV mini-grids, the same process was used, but with solar panels, battery systems and diesel generators. Pricing data for the HOMER mini-grid dimensioning simulations are presented in Table 10.

In addition to technical characteristics of the mini-grids, the visualization platform will also allow stakeholders to view cost and financial characteristics. The technical and financial characteristics will include generation, storage, supplementary capacity and MV and LV network characteristics.

Solar standalone technical assumptions

For purposes of the standalone solar PV analysis, SEforALL indicated that solar standalone service should be evaluated to achieve a tier 2 level of service. Data indicate that the vast majority of standalone solar PV in use are tier 1 equivalent systems, and therefore will need to be replaced or upgraded to achieve tier 2 service.

An implementation plan was prepared for standalone solar PV solutions, anticipating that sales will move from peri-urban to rural areas over time as the electrification programme matures. As electrification is expanded to more remote areas, government financial contributions for standalone solar solutions will need to increase to compensate for decreasing affordability. The standalone solar analysis includes component failure rates as part of the life of programme cost for standalone solar solutions. In this evaluation, batteries, controllers and lights have assumed lifespans of five years. In addition, replacement costs for standalone solar systems have been included in the financing requirements to reflect the overall programme requirements that are impacted by these component replacement requirements.

Cost Assumptions

Cost data were collected and evaluated for grid densification, grid extension, mini-grids and standalone solar systems. These are presented in the section below.

Distribution grid cost assumptions

Table 9 summarizes the unit costs used to evaluate electrification expansion costs. While JIRAMA was able to provide some cost data for 20kV and 35 kV MV networks, the data provided dated back to 2010 and thus were out of date. Rather than using the JIRAMA 2010 data to project costs in 2023, the team decided to use cost data derived from other electrification programmes in the region, to approximate unit costs for Madagascar. The cost assumptions were validated by the Ministry of Energy and Hydrocarbons (MEH) Planning Unit.

Table 9. Cost summary assumptions (Source: NRECA International 2023)

Item	Type	Size	Rate (US$)	Unit
35 kV Line	AAAC	117mm2	$33,810	$ per km
	AAAC	54.6mm2	$29,150	$ per km
35 kV Line two phase (phase to phase)	AAAC	34.4mm2	$24,849	$ per km
Transformers	35/ 0.4 three phase			
		350 kVA	$14,835	$ / Unit
		100 kVA	$11,380	$ / Unit
		50 kVA	$6,670	$ / Unit
	30/230 single phase	25kVA	$4,070	$/Unit
		15kVA	$3,520	$/Unit
20 kV Line	AAAC	117mm2	$29,400	$ per km
	AAAC	54.6mm2	$26,500	$ per km
20 kV Line two phase (phase to phase)	AAAC	34.4mm2	$22,590	$ per km
Transformers	20/ 0.4 three phase			
		200 kVA	$12,900	$ / Unit
		100 kVA	$10,800	$ / Unit
		50 kVA	$5,800	$ / Unit
	30/230 single phase	25kVA	$3,700	$/Unit
		15kVA	$3,200	$/Unit
15 kV Line	AAAC	117mm2	$28,518	$ per km
	AAAC	54.6mm2	$25,705	$ per km
Transformers	15/ 0.4 three phase			
		150 kVA	$12,513	$ / Unit
		100 kVA	$10,476	$ / Unit
		50 kVA	$5,626	$ / Unit
LV Line and Service Drops				

0.4 kV three phase twisted insulated cable with carrier neutral	ABC	95 mm2	$21,800	$ per km
0.4 kV three phase twisted insulated cable with carrier neutral	ABC	54.6mm2	$16,300	$ per km
0.23 kV self-supporting twisted insulated cable	ABC	35mm2	$12,900	$ per km
Service Drop Cost, single-phase consumers			$160	per connection
Service Drop Cost, three-phase consumers			$255	per connection
JIRAMA low-cost connection (MORA)			$80	per connection

Mini-grid assumptions

Mini-grid costs were estimated for both LV and MV mini-grids using distinct cost assumptions for each. Costs for MV mini-grids are presented in the MV column of Table 10; these mini-grids include larger power plants that in some cases have generation capacities exceeding 1 MW and serve thousands of connections. Due to significantly smaller sizes, LV mini-grids are characterized by higher unit costs shown in the LV column of Table 10. The LV mini-grids serve single, smaller communities with connections that range from 100 to 437 structures and much smaller capacities of generation plant components. Unit costs estimates were derived from industry sources and adjusted to represent expected costs during the IEP implementation timeline. The costs account for bulk procurement discounts, envisioning that mini-grid developers can buy materials in batches of a dozen or more mini-grids simultaneously using competitive pricing and streamlined logistics costs.[31]

Table 10. Cost assumptions for Madagascar IEP mini-grids

Solar Mini-grids	Units	MV Mini-Grids		LV Mini-Grids	
Solar PV Generation					
PV Modules	US$/W	$	0.23	$	0.29
PV Racking (Ground Mount)	US$/W	$	0.21	$	0.26
PV Inverters (String Inverters)	US$/W	$	0.11	$	0.14
Solar Installation Costs (Labor + PM)	US$/W	$	0.23	$	0.29
Solar Balance of System (BOS)	US$/W	$	0.09	$	0.11
Solar Logistics	US$/W	$	0.07	$	0.09
Total Solar Installed Costs	**US$/W**	**$**	**0.95**	**$**	**1.18**
Battery Energy Storage (BESS)					
Batteries (LFP, including Racks)	US$/kWh	$	345	$	431
Battery Inverter (PCS)	US$/W	$	0.16	$	0.20
Battery Installation Costs (Labour + PM)	US$/W	$	0.08	$	0.10
BESS Balance of System (BOS)	US$/W	$	0.05	$	0.06
BESS Logistics	US$/W	$	0.05	$	0.06
Total Battery Installed Costs	**US$/kWh**	**$**	**430**	**$**	**537**

[31] The costs are derived from ESMAP reports and are also used by the Demand Aggregation for Renewable Technologies programme funded by GEAPP.

Diesel Genset (DG)					
Genset Cost (with sync controller)	US$/W	$	0.35	$	0.39
Installation Cost (with synchronization)	US$/W	$	0.15	$	0.17
Fuel Tank, Piping, Filters, BOS	US$/W	$	0.06	$	0.07
Genset Logistics	US$/W	$	0.05	$	0.06
Total Genset Installed Costs	**US$/W**	**$**	**0.61**	**$**	**0.67**
Balance of System Costs					
Containerized Powerhouse	US$/W	$	0.23	$	0.29
Unloading and installation	US$/W	$	0.04	$	0.05
Logistics for Enclosure	US$/W	$	0.03	$	0.04
Civil Works, Fencing, Access Road	US$/W	$	0.02	$	0.03
Mini-grid Controller (MGC)[32]	**US$/Unit**	**$**	**30,000**	**$**	**10,000**
Metering Server, Modem, Comms	**US$/Unit**	**$**	**7,500**	**$**	**2,500**

The costs presented in the study represent costs for mini-grid infrastructure, equipment and installation. Private-sector mini-grid developers will also incur costs associated with project development that are not included here. These costs include business registration, staff salaries, vehicles, mini-grid licensing, due diligence and other associated expenses that are attributable to the mini-grid assets themselves.

Standalone solar

The base case analysis for electrification by 2030 includes a minimum of tier 2 standalone solar systems for universal electrification. The costs required for providing rural households with standalone solar systems include not only the cost of the tier 2 standalone solar systems but also sales, general and administrative (SG&A) costs. They also include customer acquisition and service costs for meeting the needs of a low-density customer base in remote areas. Based on a review of standalone solar system (SSS) distributors and retailers, this cost was estimated to be USD 350 per tier 2 sstem. Tier 2 standalone solar systems have at least 50 W of solar capacity and at least 200 Wh of battery capacity. They are generally roof-mounted units with multiple lights and DC outlets or charging ports for mobile phones, radios, etc.[33]

A sensitivity analysis was conducted with tier 1 standalone solar systems being interpreted as sufficient for universal access. Based on a similar review of standalone solar system distributor activity, the full cost of a tier 1 system was estimated to be USD 180. Tier 1 standalone solar systems have at least 3 W of solar capacity and at least 12 Wh of battery capacity. They can be roof or ground mounted roughly with a small footprint with multiple points of light, a service outlet and USB-mobile phone charging capability.[34]

[32] Developers may have varied approaches to to mini-grid control systems; in practice, industry solutions may range from USD 0 (utilizing the native inverter monitoring platform, i.e. Victron) to over USD 100,000 for a fully integrated SCADA solution, This assumption is intended to comprise the SCADA or DAS system that enables remote monitoring and generation dispatch for all assets in the mini-grid power station. It assumes an on-site computer, cell modem, network switch and integrated mini-grid firmware to securely communicate with all generation/storage sources and inverters. For MV mini grids, it includes generator synchronization.

[33] For more information on standalone solar system sizing and characteristics: https://mtfenergyaccess.esmap.org/methodology/electricity

[34] More information on the Multi Tier Framework (MTF) for energy access can be found on the ESMAP website. https://mtfenergyaccess.esmap.org/methodology/electricity

MADAGASCAR ELECTRIFICATION SCENARIOS

Two scenarios are analyzed in the electrification component; the first focuses on achieving universal access by 2030 and is considered the base case for this study. Considering Government of Madagascar (GoM) financing constraints and the practical limitations of electrification expansion, a second, more conservative, scenario is evaluated to roll out investments in grid expansion and mini-grid development to achieve universal electricity access by 2040. In deriving the universal access electrification model, NRECA considered incremental milestones by electrification modality including existing connections, grid densification, grid expansion, mini-grids and standalone solar systems. The minimum level of service is defined in each scenario using the Multi-Tier Framework for Electricity Access" a commonly accepted international standard that defines various standardized levels of access to electricity and associated services as shown in the table below.

Figure 11. Multi-Tier Framework for Electricity Access

ATTRIBUTIONS			NIVEAU 0	NIVEAU 1	NIVEAU 2	NIVEAU 3	NIVEAU 4	NIVEAU 5
	1. Capacité de pointe	Puissance nominale (en W ou Wh par jour)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
				Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
		Services OR		Éclairage de 1 000 lmh/jour	L'éclairage électrique, l'air, la circulation, la télévision et la recharge du téléphone sont possibles.			
	2. Disponibilité (Durée)	Nombre d'heures par jour		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
		Nombre d'heures par soir		Min 1 hrs	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
	3. Fiabilité						Max 14 perturbations par semaine	Max 3 perturbations par semaine de durée totale <2hrs

Adapté du rapport de la Banque mondiale/ESMAP, Au-delà des connexions : Accès à l'énergie redéfini, 2015.

In the base case analysis, the model considers a minimum of tier 2 electrification based on the ESMAP Multi-Tier Framework (MTF). Additionally, the base case scenario includes no improvements or hybridization to the existing JIRAMA isolated systems, but new mini-grids were considered with both MV and LV distribution networks and renewable energy generation plants including solar or hydro with energy storage and no diesel generation. The two scenarios analyzed are presented in Table 11.

Table 11. Electrification scenarios

Scenario	Universal access to electricity achieved in:	Common scenario characteristics	Sensitivities to the base case
Scenario 1 (Base case) **SDG7 Baseline**	2030	– Tier 2 minimum quality of service – All off-grid electrification (mini-grids and standalone systems) are solar PV with 100% RE fraction	– Tier 1 minimum quality of service – Allow diesel back-up generation for mini-grids – +/- 15% electricity consumption – Consider all mini-grids as 75% renewable fraction
Scenario 2 **Universal access by 2040**	2040		None

LEAST-COST ELECTRIFICATION ANALYSIS

The geospatial model was used to identify and evaluate grid and off-grid project options to serve unelectrified communities throughout Madagascar. Adjustments in results were made to balance grid and off-grid investment programmes, taking into consideration the scope and capacity of interconnected and isolated distribution networks, as well as affordability and the ability of the public- and private-sector resources to finance the investments.

Densification

Analysis of densification potential is a process of identifying all potential consumers within reach of low voltage (LV) service and comparing this figure to the total number of consumers presently served via the distribution system to determine the cost of and benefit from increasing connected consumers. Densification costs include the cost of a service connection (up to 50 meters of triplex conductor, a weatherhead, and a single-phase revenue meter) with less than 10 meters of LV line and an allowance for 1/100th of additional transformer capacity related to each new consumer connection. Densification costs were aggregated by JIRAMA service centres; additional transformer capacity was evaluated to define the number of new transformers required. The estimated cost of densification is USD 375.

Densification analysis was performed using digitized housing structure data with medium voltage (MV) distribution system infrastructure data. Densification is normally performed by evaluating consumer potential within a defined distance from existing distribution transformers, but at the time of this study, JIRAMA did not yet have geographically located distribution transformers. Due to this limitation, the densification analysis was evaluated by creating a 600-meter buffer around the entire MV network in conjunction with the 2022 JIRAMA customer database.

Households connected via grid densification will increase energy consumption and contribute to an increase in peak demand. Nevertheless, incremental generation expansion and fuel costs were excluded from densification costs for the purposes of the analysis. The most significant densification potential is associated with isolated grids where connected consumers can be increased by nearly a factor of four.

Densification results by district are shown in Table 12. Densification activities were assumed to start in 2024 and increase as momentum grows through the duration of the planning horizon to meet the target of universal electrification by 2030. JIRAMA will require time to increase staffing and build capacity, so the programme is expected to achieve maximum densification rate by 2028–2029 as shown in Figure 12.

As presented in the overview section, JIRAMA reported 620,839 customers in 2022, of which 95 percent are residential. Data provided by JIRAMA indicate that approximately 100,501 consumers were connected between 2018 and 2022, at a rate of about 20,000 per year. No data are available on the proportion of new connections through grid densification or grid expansion; however, discussions with JIRAMA officials indicated that most new connections in recent years were through grid densification, where the vast majority of new connections are customer-requested short LV extensions/new service drop. Table 12 provides an overview of the digitized structures per district served by JIRAMA, then the number of assumed electrified structures and then the densification potential in electrifiable structures.

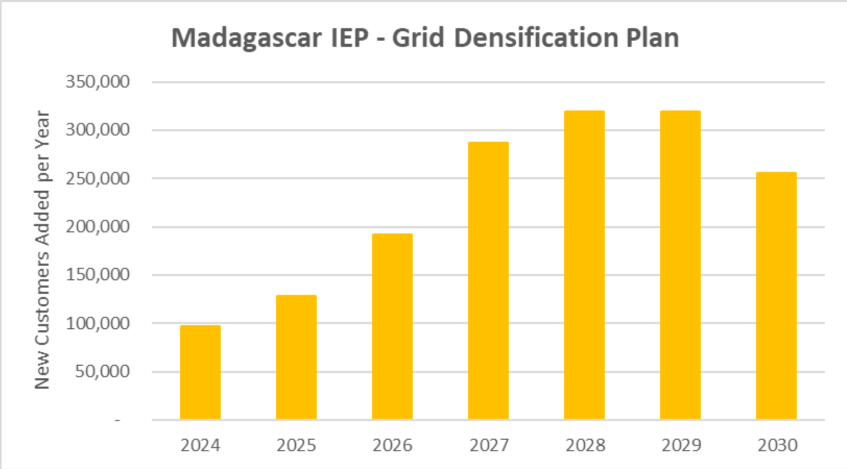
Table 12. Densification potential by district

District	Structures (2023)	Assumed electrified JIRAMA structures (2023)	Densification Potential (2023)
1er Arrondissement (Antananarivo)	34,571	11,997	22,574
2e Arrondissement (Antananarivo)	37,420	12,985	24,435
3e Arrondissement (Antananarivo)	21,831	7,576	14,255
4e Arrondissement (Antananarivo)	46,274	16,058	30,216
5e Arrondissement (Antananarivo)	66,197	22,971	43,226
6e Arrondissement (Antananarivo)	32,814	11,387	21,427
Ambalavao	8,658	2,380	6,278
Ambanja	23,726	4,646	19,080
Ambato Boeni	4,024	883	3,141
Ambatolampy	20,054	6,959	13,095
Ambatomainty	1,746	359	1,387
Ambatondrazaka	23,909	7,997	15,912
Ambilobe	20,674	3,706	16,968
Amboasary-Atsimo	5,100	719	4,381
Ambohidratrimo	149,259	51,795	97,464
Ambohimahasoa	3,730	1,025	2,705
Ambositra	4,970	4,769	201
Ambovombe-Androy	11,241	1,205	10,036
Ampanihy Ouest	2,248	1,328	920
Amparafaravola	8,106	2,231	5,875
Analalava	1,367	586	781
Andapa	13,440	2,322	11,118
Andilamena	4,998	1,155	3,843
Andramasina	4,222	1,465	2,757
Anjozorobe	2,221	632	1,589
Ankazoabo	2,028	840	1,188
Ankazobe	1,471	510	961
Anosibe-An'ala	916	621	295
Antalaha	19,711	5,206	14,505
Antananarivo Atsimondrano	185,199	64,267	120,932
Antananarivo Avaradrano	169,325	58,759	110,566

Antanifotsy	40	-	40
Antsalova	1,143	277	866
Antsirabe I	86,541	30,031	56,510
Antsirabe II	30,300	10,515	19,785
Antsiranana I	38,354	18,750	19,604
Antsiranana II	5,837	671	5,166
Antsohihy	9,063	3,154	5,909
Arivonimamo	44,691	15,509	29,182
Bealanana	7,126	1,098	6,028
Befandriana Nord	5,897	1,289	4,608
Bekily	1,631	-	1,631
Belo Sur Tsiribihina	4,302	938	3,364
Beloha	1,892	304	1,588
Betafo	10,474	3,635	6,839
Betioky Atsimo	6,913	1,130	5,783
Brickaville	4,136	1,219	2,917
Fandriana	5,962	-	5,962
Farafangana	7,860	2,463	5,397
Faratsiho	8,544	2,965	5,579
Fenerive Est	19,368	3,749	15,619
Fianarantsoa I	48,941	13,452	35,489
Ihosy	13,635	3,298	10,337
Isandra	984	-	984
Lalangina	11,944	3,283	8,661
Maevatanana	6,247	1,338	4,909
Mahabo	6,146	-	6,146
Mahajanga I	78,248	25,745	52,503
Mahajanga II	3,945	-	3,945
Maintirano	4,265	1,842	2,423
Mampikony	7,470	1,327	6,143
Manakara Atsimo	9,593	4,296	5,297
Mananara-Avaratra	15,955	2,306	13,649
Mananjary	3,752	3,204	548
Mandoto	1,738	-	1,738
Mandritsara	8,568	960	7,608
Manja	2,534	562	1,972
Manjakandriana	33,099	11,486	21,613
Maroantsetra	16,739	4,390	12,349
Marovoay	7,735	2,385	5,350
Miandrivazo	3,763	869	2,894
Miarinarivo	23,487	8,150	15,337
Mitsinjo	1,117	353	764

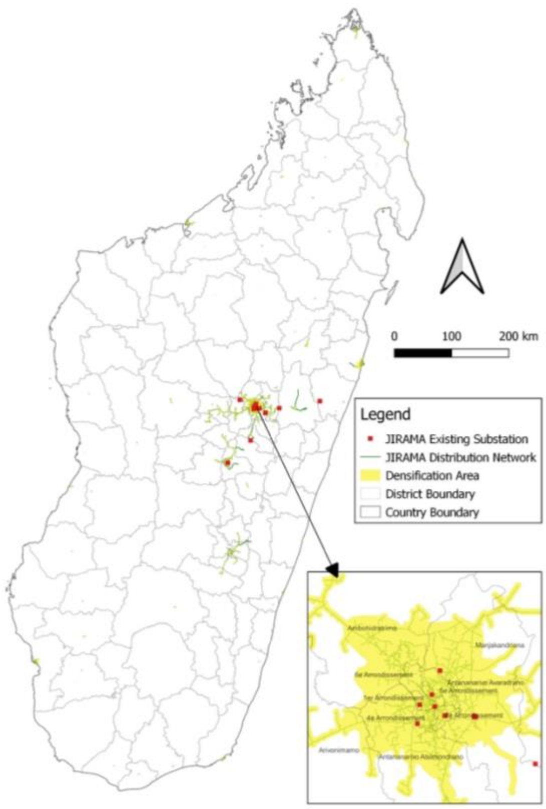
Morafenobe	808	301	507
Moramanga	22,371	-	22,371
Morombe	5,213	877	4,336
Morondava	12,210	4,860	7,350
Nosy-Be	12,796	10,574	2,222
Port-Berge (Boriziny-Vaovao)	7,673	1,420	6,253
Sakaraha	5,131	1,493	3,638
Sambava	47,841	6,091	41,750
Soanierana Ivongo	2,869	1,078	1,791
Soavinandriana	12,506	4,340	8,166
Taolagnaro	16,749	4,910	11,839
Toamasina I	83,414	30,232	53,182
Toamasina II	29,796	10,799	18,997
Toliary-I	59,935	18,690	41,245
Toliary-II	30,598	-	30,598
Tsaratanana	2,295	455	1,840
Tsihombe	3,042	360	2,682
Tsiroanomandidy	11,180	3,307	7,873
Vangaindrano	3,093	1,363	1,730
Vatomandry	3,468	1,680	1,788
Vavatenina	5,498	1,243	4,255
Vohemar	18,447	2,723	15,724
Vohibato	6,832	1,878	4,954
Vohipeno	2,531	747	1,784
Total	**1,947,735**	**605,851**	**1,341,884**

Figure 12. Rate of densification by year



The densification results are also presented by region in Figure 13. Densification potential is highest in the urban and peri-urban areas of Madagascar. Analamanga, the region that includes Antananarivo, accounts for 38 percent of the densification potential of the entire country. In areas where JIRAMA has little or no electricity service, densification potential is minimal. Therefore, densification alone will not provide broadly inclusive and equitable electrification outcomes – it must be complemented by the other electrification modalities. Figure 13 illustrates densification potential throughout Madagascar.

Figure 13. Illustration of grid densification potential by geographic zone

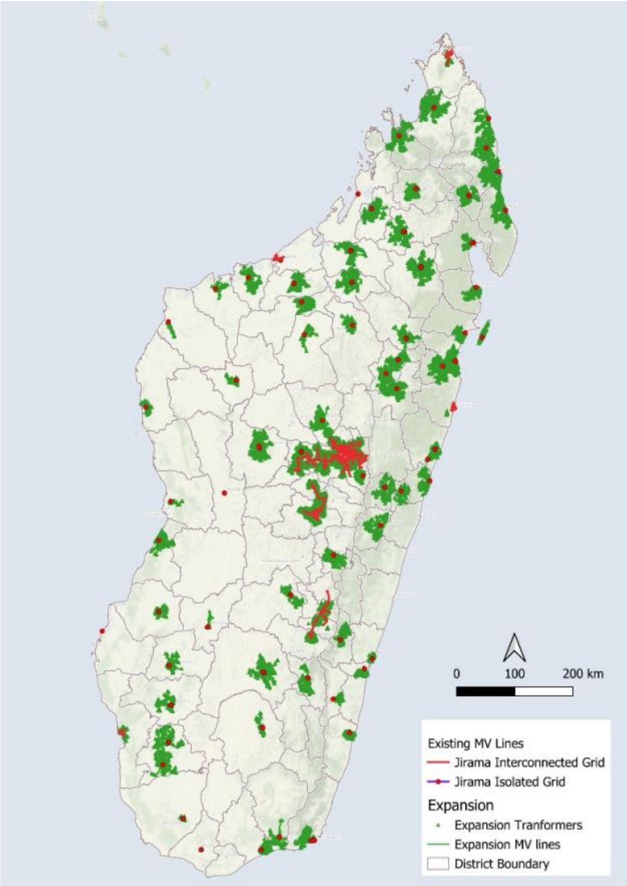


Grid Expansion

Grid expansion is the process of extending medium voltage (MV) service beyond the existing distribution system footprint to unelectrified communities and housing clusters. Grid expansion analysis was performed for all JIRAMA service areas including interconnected and isolated grids. For the purposes of this analysis, it was assumed that the PRIRTEM I project timeline has been confirmed but that phases II and III would be excluded due to uncertainties about funding and completion dates. JIRAMA operates 96 isolated grids across Madagascar, which represents the third largest mini-grid portfolio of any public utility globally, behind only the Philippines and Russia.[35]

Evaluation of grid expansion involves clustering structures, defining the capacities of the distribution transformers that will serve these clusters, and routing MV line extensions to the transformers. The geospatial model aggregates the structures, evaluates demand of each housing cluster and evaluates transformer capacity and conductor sizes for all MV interconnecting lines. Figure 14 illustrates the expansion process, where existing MV lines (shown in red) are extended (shown in green) to interconnect new transformer placements. Figures 15 and 16 show grid expansion results for RIA and RIF JIRAMA grid systems.

Figure 14. Grid expansion results



[35] ESMAP, Mini Grids for Half a Billion People, 2022.

Figure 15. RIA grid expansion results

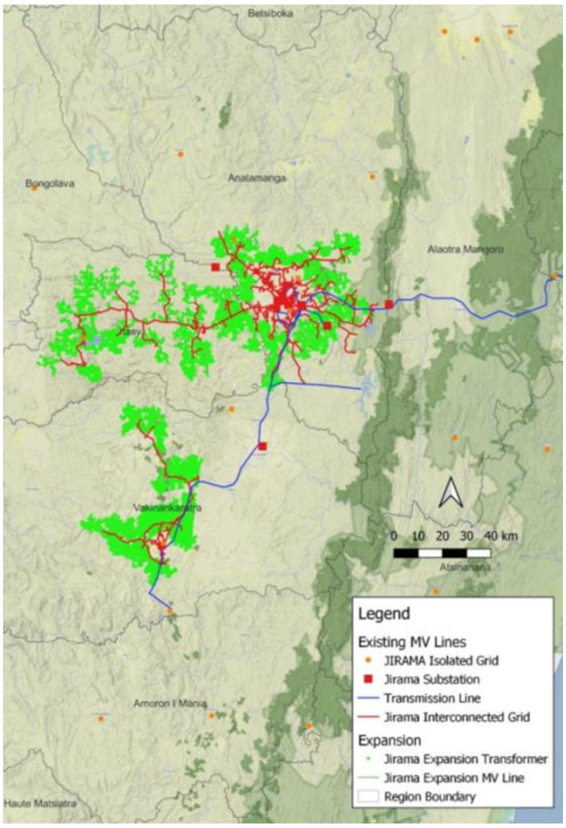
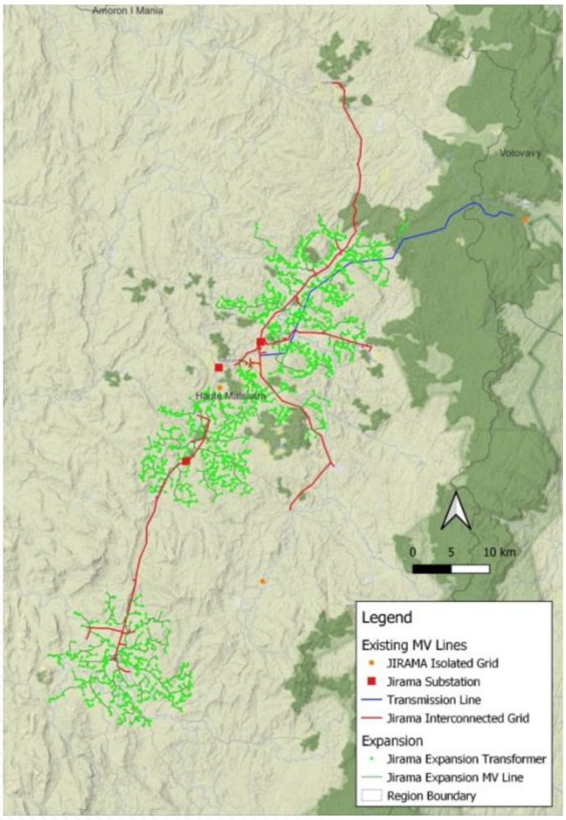


Figure 16. RIF grid expansion results



Project characteristics – pole locations, MV line length, conductor size, energy consumption and demand – were evaluated in detail for all expansion projects.. Capital costs for each project were calculated using the unit cost data as an input parameter in the platform. All this information was embedded in the geographic database and can be exported to facilitate detailed load flow and other analyses for each project, substation and distribution segment. These and other assumptions are presented in Annex A1 while Annex B1 provides a list of all grid expansion projects.

Table 13 presents the results of grid expansion by region. These projects have costs that are below USD 1,250 per connection that is the limit applied to grid expansion projects for the Madagascar IEP and limited to no more than 15 km from the tapping point for each project. Projects have been aggregated into three project packages based on average cost per connection. These packages are as follows:

Lot 1: Projects below USD 700 per connection. Construction timeline 2024–2027.

Lot 2: Projects between USD 700–USD 1,000 per connection. Construction timeline 2026–2029.

Lot 3: Projects above USD 1000 per connection. Construction timeline 2027–2030.

Table 13. Grid expansion potential by district

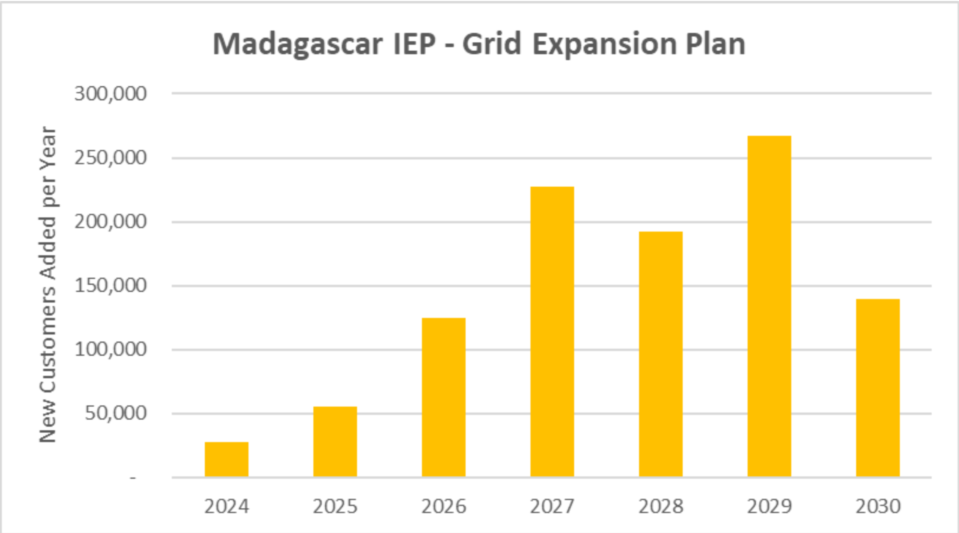
District	Lot 1 Connections	Lot 2 Connections	Lot 3 Connections	Total Connections
Ambalavao	0	0	13512	13512
Ambanja	21691	0	1988	23679
Ambato Boeni	0	6385	0	6385
Ambatolampy	0	0	5655	5655
Ambatomainty	0	3099	0	3099
Ambatondrazaka	14338	0	0	14338
Ambilobe	0	15524	2927	18450
Amboasary-Atsimo	0	5066	208	5274
Ambohidratrimo	0	21216	21323	42539
Ambositra	0	6810	7448	14258
Ambovombe-Androy	0	2803	3797	6600
Ampanihy Ouest	3922	0	1293	5215
Amparafaravola	34970	7243	0	42213
Analalava	0	43	0	43
Andapa	39451	177	0	39628
Andilamena	9229	3720	577	13526
Andramasina	0	0	8518	8518
Ankazoabo	0	0	6562	6562
Ankazobe	0	11191	8568	19758
Anosibe-An'ala	0	4767	708	5476
Antalaha	15297	4180	0	19477
Antanambao Manampontsy	0	0	2624	2624

Antananarivo Atsimondrano	8791	6721	190	15702
Antananarivo Avaradrano	9465	12083	195	21743
Antsirabe I	0	1965	371	2335
Antsirabe II	0	56130	24489	80619
Antsiranana I	0	0	371	371
Antsiranana II	0	0	2776	2776
Antsohihy	0	7251	0	7251
Arivonimamo	0	38645	22036	60681
Bealanana	2007	0	5600	7607
Befandriana Nord	4977	0	4090	9067
Belo Sur Tsiribihina	0	0	1014	1014
Beloha	0	0	563	563
Beroroha	2630	132	0	2763
Besalampy	2560	0	0	2560
Betafo	0	24500	4798	29298
Betioky Atsimo	2944	852	9101	12898
Betroka	5716	549	881	7146
Brickaville	0	0	7948	7948
Faratsiho	0	0	17235	17235
Fenerive Est	2326	18564	0	20889
Fianarantsoa I	0	797	543	1340
Ihosy	948	8818	2393	12159
Ikalamavony	2408	1310	1419	5138
Ikongo	46	0	6296	6342
Ivohibe	1573	1022	1524	4119
Lalangina	0	18911	7549	26459
Maevatanana	2477	2669	0	5146
Mahajanga I	0	0	345	345
Maintirano	0	0	3093	3093
Mampikony	0	8909	4974	13883
Manakara Atsimo	0	0	6150	6150
Mananara-Avaratra	18317	0	55	18372
Mandritsara	0	7723	4177	11900
Manja	0	0	4748	4748
Manjakandriana	0	0	29935	29935
Maroantsetra	5942	1042	0	6984
Marolambo	623	3976	593	5192
Marovoay	0	9466	0	9466
Miarinarivo	0	17361	28874	46234
Mitsinjo	0	0	3242	3242
Morondava	0	10527	0	10527
Port-Berge (Boriziny-Vaovao)	0	9625	0	9625
Sainte Marie	7714	1863	0	9577
Sakaraha	1375	0	3440	4816
Sambava	15596	5315	0	20911

Soalala	0	0	751	751
Soanierana Ivongo	0	3734	358	4092
Soavinandriana	0	6049	11243	17292
Taolagnaro	0	0	4273	4273
Toamasina II	0	0	915	915
Toliary-I	758	532	0	1290
Toliary-II	5800	0	3366	9166
Tsaratanana	5720	1863	0	7583
Tsiroanomandidy	0	0	5837	5837
Vangaindrano	0	5209	7952	13161
Vatomandry	0	3105	823	3928
Vavatenina	14570	8053	0	22622
Vohemar	14207	2649	924	17781
Vohibato	0	0	14571	14571
Vohipeno	0	6827	170	6997
Vondrozo	246	60	464	770
Grand Total	**278,634**	**407,034**	**348,360**	**1,034,027**

These projects will serve approximately 1 million new consumers with an average cost of USD 890 per connection. The construction timeline for grid expansion lots is presented in Figure 17. If all potentially electrifiable customers were energized by 2030, this would add an additional demand of 193 MW using the monthly electricity consumption rate per structure provided in the routing rule section.

Figure 17. Annual grid expansion connections per year

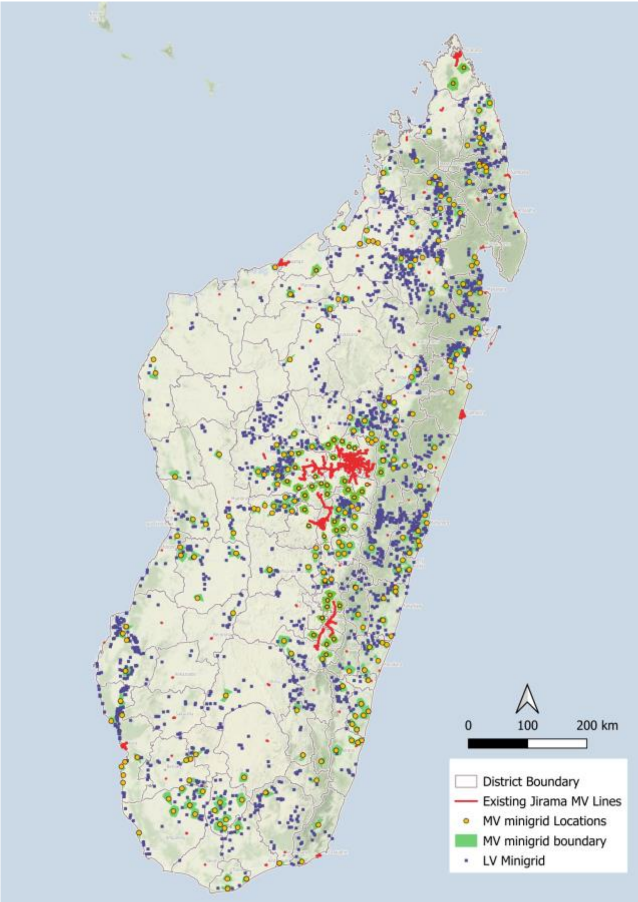


Mini-grids

All areas beyond the reach of grid expansion were evaluated for off-grid electrification. The off-grid market can be segmented into those communities with population density sufficiently high to support mini-grid systems and the rest of Madagascar where standalone solar solutions are mostly likely to be used for lighting, mobile phone charging and other energy needs. Unlike countries with national transmission networks connecting central-station power plants to load centres, Madagascar has not yet developed a national transmission network. In its place, three regional transmission networks provide transmission service in central Madagascar with limited service to northern and southern regions. This has resulted in long MV line extensions in some areas of Madagascar that result in problematic power quality.

Thus, to better align the IEP with pragmatic electrification practices, grid expansion was limited to serve communities that require no more than 15 km of MV network to interconnect. As a result, the mini-grid electrification modality will comprise some peri-urban areas and small, remote communities. To characterize these differences, the mini-grid projects are classified as: (a) grid edge MV mini-grids,[36] (b) isolated MV mini-grids and (c) LV mini-grids.

Figure 18. Map of both LV and MV mini-grids



[36] "Grid edge" refers to mini-grids that provide service in high-density peri-urban areas that would require more than 15 km of MV line extension from the edge of JIRAMA service. For purposes of grid expansion analysis, JIRAMA grid expansion analysis of the 20 kV network was limited to 15 km of addition MV line construction given concerns with power quality beyond this modest limit. Expansion of 20 kV lines beyond 15 km could lead to significant power quality issues such as excessive voltage drop, increased thermal losses and increases in reactive power loss near the end of the line.

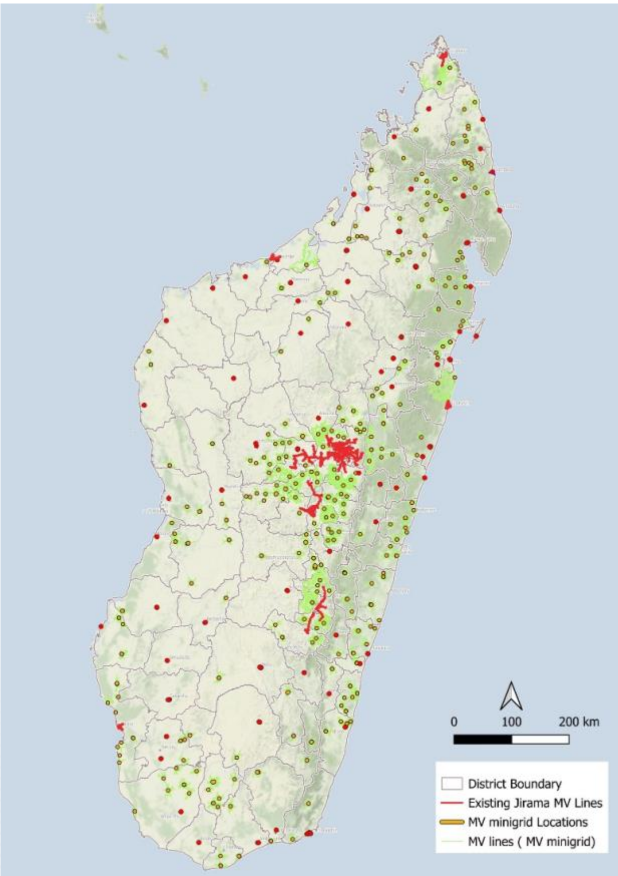
MV Mini-grids

MV distribution is used to interconnect rural communities with larger service territories than can be reliably served by LV infrastructure. Namely, population zones with a radius of larger than 600 meters. By adopting an MV topology these customers will be served by a central generation source whose power output will be stepped up to MV distribution voltage and then stepped down via distribution transformers to LV lines to connect electricity consumers.

Alternately, each of the distribution transformers could be the site of a power plant to power these customers as an isolated LV mini-grid, but for purposes of the Madagascar IEP, there are strategic advantages and economies of scale to be gained by connecting large clusters of unelectrified consumers via a MV network. Nevertheless, significant safety challenges are associated with operating MV distribution systems in rural areas of developing economies that require training and oversight programmes. Use of MV network infrastructure requires extensive safety training and skills development for line workers responsible for operations and maintenance of network systems.

The MV mini-grids are categorized as either grid edge MV mini-grids or isolated MV mini-grids. All are illustrated in Figure 19.

Figure 19. Map for MV mini-grids



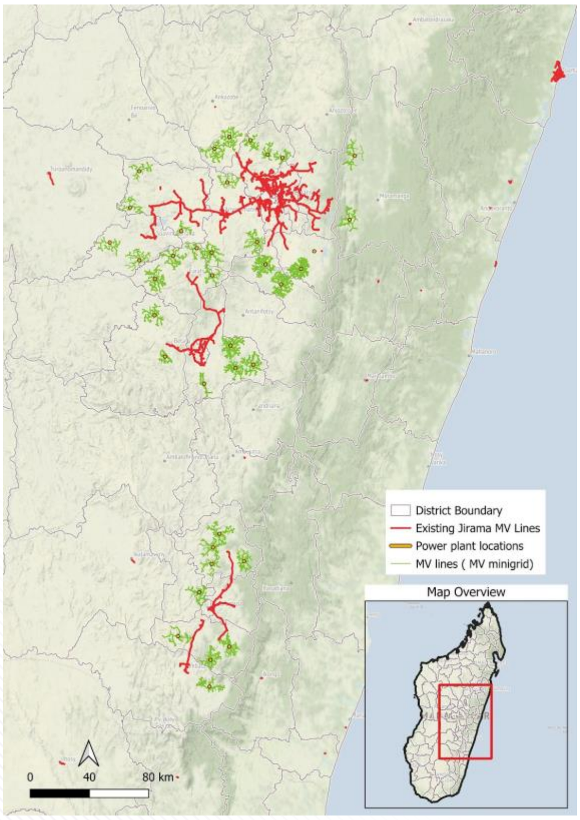
Grid-Edge MV Mini-grids

"Grid edge" refers to mini-grids that provide service in high density peri-urban areas, that would require more than 15 km of MV line construction from the edge of JIRAMA service. For purposes of grid-expansion analysis, JIRAMA grid-expansion analysis of the 20 kV network was limited to 15 km of additional MV extension given concerns with power quality beyond this modest limit. Expansion of 20 kV lines beyond 15 km could lead to significant power quality issues such as excessive voltage drop, increased thermal losses and increases in reactive power loss near the end of the line.

Therefore, housing clusters requiring MV line construction from existing JIRAMA service of less than or equal to 15 km will be served by grid extension while those beyond 15 km will be evaluated for mini-grid service. Grid-edge mini-grids will require associated generation stations to independently provide all required power supply to consumers in these mini-grids. Should JIRAMA build new substations or engage distributed generation suppliers, the grid edge mini-grids could purchase or sell power supply through JIRAMA. However, for the purposes of this analysis, it is assumed that grid-edge mini-grids will independently invest in ring-fenced power supply.

In the base case, grid-edge mini-grids derive power from solar, battery and diesel hybrid power plants. The costs associated with procurement, deployment and installation of these grid-edge power plants are included in the budget for 2030 universal electrification. Figure 20 illustrates grid-edge mini-grids, including their service territories and indicative power plant locations.

Figure 20. Map showing examples of grid-edge MV mini-grids

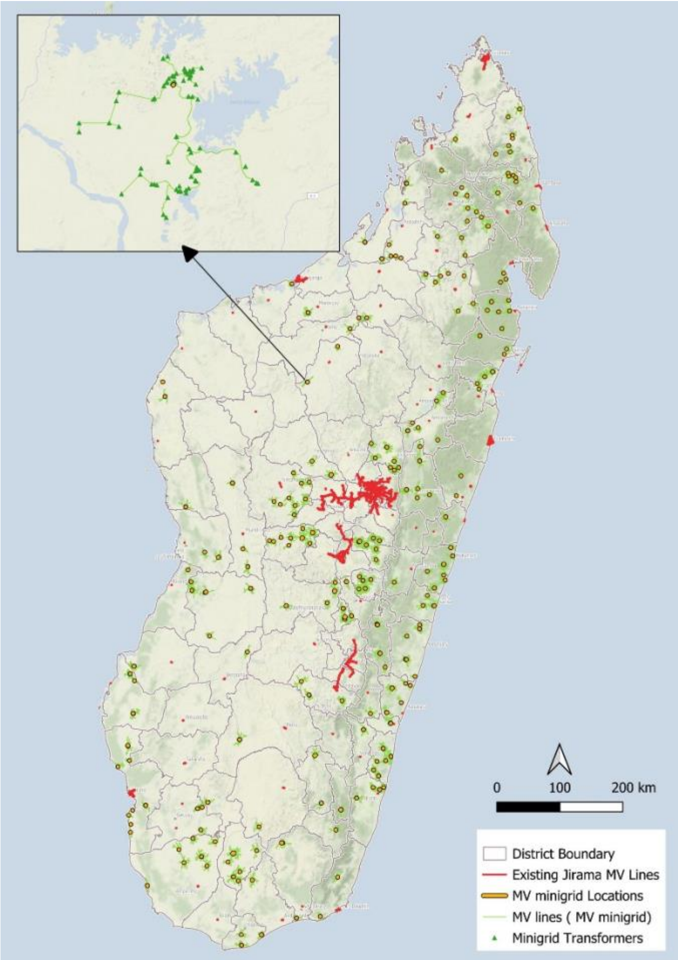


Isolated MV Mini-grids

Isolated MV mini-grids are located beyond the 15 km limit of JIRAMA grid networks in rural areas of Madagascar. There are many areas in Madagascar where sufficient population density exists for electric utility service, but where JIRAMA does not yet offer electricity service. Communities in these areas have been evaluated for isolated mini-grid development with on-site power generation and either MV or LV distribution networks. MV isolated grids are also sometimes referred to as "metro-grids" due to larger power generation capacity and associated larger communities that are served. The terminology used for purposes of the IEP is isolated MV mini-grids.

When considered collectively, the MV mini-grids are diverse geographically and technically. The smallest MV mini-grids have slightly over 100 consumers and peak demand in the same range as the LV mini-grids. The larger MV mini-grids may have a peak demand of several megawatts. MV mini-grids have been designed with solar-diesel hybrid technology optimized for levelized cost of energy (LCOE) that generally results in a renewable fraction over 85 percent but that relies on diesel generation to supplement solar generation when necessary. Of the 397 MV mini-grids in the model, 295 are anticipated to have more than 1,000 consumers by 2030. Many of these MV mini-grid candidates could host successful small utility companies, provided that the regulatory and subsidy environment is favourable for rural utilities. Figure 21 illustrates isolated mini-grids identified and evaluated in the geospatial modelling framework.

Figure 21. Isolated mini-grids, including detailed view of Maevatanana district, Betsiboka region



A summary of MV mini-grids characteristics by district is provided in Table 14. The MV mini-grids were organized into three implementation packages referred to below as lots 1, 2 and 3. The Lot 1 MV mini-grids were selected for near-term implementation due to the interest private sector investors are likely to express in developing these projects. The Lot 3 mini-grids are likely to require significant subsidies to implement that may result in longer lead times for development and implementation. The criteria used to organize the mini-grids are as follows:

Lot 1: Total CAPEX per connection below USD 1500, construction anticipated 2025–2028. There are a total of 105 MV mini-grids in Lot 1 comprising 549,380 connections over four years, an average of 5,232 connections per mini-grid.

Lot 2: Total CAPEX per connection between USD 1500 and USD 2000, construction anticipated 2026–2029. There are 141 MV mini-grids in Lot 2 comprising 524,356 connections over four years, an average of 3,719 connections per mini-grid.

Lot 3: Total CAPEX per connection above USD 2000, construction anticipated 2027–2030. There are 125 MV mini-grids in Lot 3 comprising 361,301 connections over four years, an average of 2,890 connections per mini-grid.

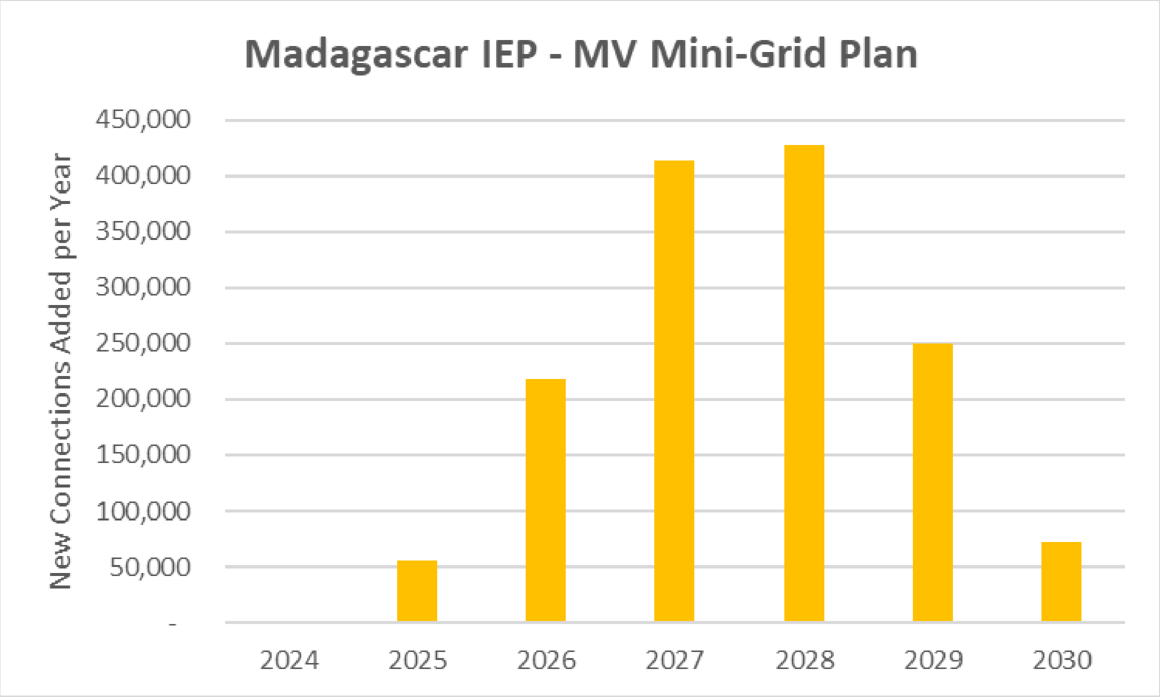
Table 14. MV mini-grids by district

District	Lot 1 Connections (2030)	Lot 2 Connections (2030)	Lot 3 Connections (2030)	Total Connections (2030)	Total MV Mini-Grids (2030)
Ambalavao	5,992	-	-	5,992	1
Ambanja	6,383	6,389	-	12,773	2
Ambato Boeni	-	27,583	13,774	41,357	3
Ambatolampy	-	4,469	2,752	7,220	10
Ambatomainty	-	7,850	-	7,850	1
Ambatondrazaka	-	-	11,219	11,219	3
Ambilobe	-	-	24,354	24,354	4
Amboasary-Atsimo	-	4,696	491	5,188	3
Ambohidratrimo	-	2,464	1,610	4,074	2
Ambohimahasoa	-	17,619	11,158	28,777	12
Ambositra	3,771	-	-	3,771	1
Ambovombe-Androy	12,847	4,406	1,391	18,644	7
Ampanihy Ouest	16,622	-	-	16,622	2
Analalava	-	-	372	372	1
Andramasina	-	-	3,480	3,480	1
Ankazoabo	-	-	1,515	1,515	1
Antanambao Manampontsy	-	9,468	14,435	23,903	4
Antananarivo Atsimondrano	23,886	13,681	-	37,566	6
Antananarivo Avaradrano	-	11,997	8,470	20,467	5
Antanifotsy	13,762	40,042	11,480	65,284	9
Antsalova	-	903	859	1,763	2
Antsirabe I	7,431	-	-	7,431	1
Antsiranana I	6,204	-	5,294	11,498	2
Antsiranana II	-	10,434	22,523	32,957	4
Antsohihy	10,369	-	5,753	16,122	2
Arivonimamo	8,510	3,015	-	11,525	4
Bealanana	-	13,148	18,287	31,436	3
Befandriana Nord	14,280	11,363	913	26,556	7
Befotaka	31,727	-	940	32,667	7
Bekily	-	1,900	841	2,740	2
Belo Sur Tsiribihina	1,484	39,363	1,614	42,461	19
Beloha	-	-	845	845	1
Benenitra	3,758	3,412	-	7,170	3
Besalampy	18,566	-	-	18,566	3
Betafo	-	1,793	216	2,009	2
Betioky Atsimo	-	-	323	323	1
Brickaville	15,475	1,868	-	17,343	4
Fandriana	-	6,291	-	6,291	1
Farafangana	-	3,335	-	3,335	1
Faratsiho	-	-	43,277	43,277	5
Fenerive Est	3,078	7,599	-	10,677	4
Fianarantsoa I	12,512	9,179	15,053	36,744	8
Iakora	124	-	420	544	2
Ifanadiana	-	2,256	1,035	3,291	2

Ikongo	-	2,196	-	2,196	1
Isandra	-	-	7,586	7,586	2
Lalangina	10,451	-	-	10,451	1
Maevatanana	2,857	3,015	17,014	22,886	8
Mahajanga II	-	5,054	-	5,054	1
Mahanoro	9,761	20,299	3,783	33,843	12
Maintirano	9,448	-	-	9,448	1
Mampikony	-	22,099	812	22,912	7
Manakara Atsimo	15,343	15,951	-	31,294	7
Mananara-Avaratra	255	5,237	3,212	8,705	10
Manandriana	2,286	3,332	2,960	8,577	8
Mananjary	13,507	31,969	175	45,651	15
Mandoto	31,588	-	-	31,588	7
Mandritsara	5,513	4,052	-	9,565	2
Manja	10,951	2,216	-	13,167	4
Manjakandriana	5,591	16,297	4,201	26,089	10
Maroantsetra	779	2,456	1,649	4,884	5
Marovoay	17,028	10,636	22,514	50,178	10
Miandrivazo	20,761	4,549	-	25,310	3
Miarinarivo	-	2,431	-	2,431	1
Mitsinjo	3,609	11,624	692	15,925	5
Morafenobe	-	5,628	8,581	14,208	3
Nosy-Varika	39,278	-	-	39,278	6
Port-Berge (Boriziny-Vaovao)	-	839	-	839	1
Sainte Marie	42,579	-	-	42,579	5
Sakaraha	-	-	9,290	9,290	1
Soalala	5,361	2,979	-	8,340	3
Soanierana Ivongo	7,251	815	580	8,645	4
Soavinandriana	-	5,997	-	5,997	2
Toamasina I	-	5,596	4,116	9,712	2
Toamasina II	-	13,461	16,558	30,019	7
Toliary-I	-	3,840	1,614	5,454	4
Tsaratanana	3,741	-	574	4,315	2
Tsihombe	32,626	6,287	-	38,912	10
Vangaindrano	32,189	22,418	1,909	56,516	9
Vatomandry	-	3,633	19,749	23,382	5
Vavatenina	1,093	8,392	1,543	11,028	8
Vohibato	8,753	14,533	-	23,286	7
Vohipeno	-	-	6,203	6,203	2
Vondrozo	-	-	1,275	1,275	2
Total	**549,380**	**524,356**	**361,282**	**1,435,019**	**371**

The anticipated construction timeline for MV mini-grids is presented in Figure 22. Due to the larger and more complex nature of MV mini-grids, these projects will require more time to plan, finance and build than smaller LV mini-grids Therefore, it is not anticipated that any of these systems will be completed in 2024 and the three lots described above will commence no earlier than 2025.

Figure 22. MV mini-grid implementation schedule

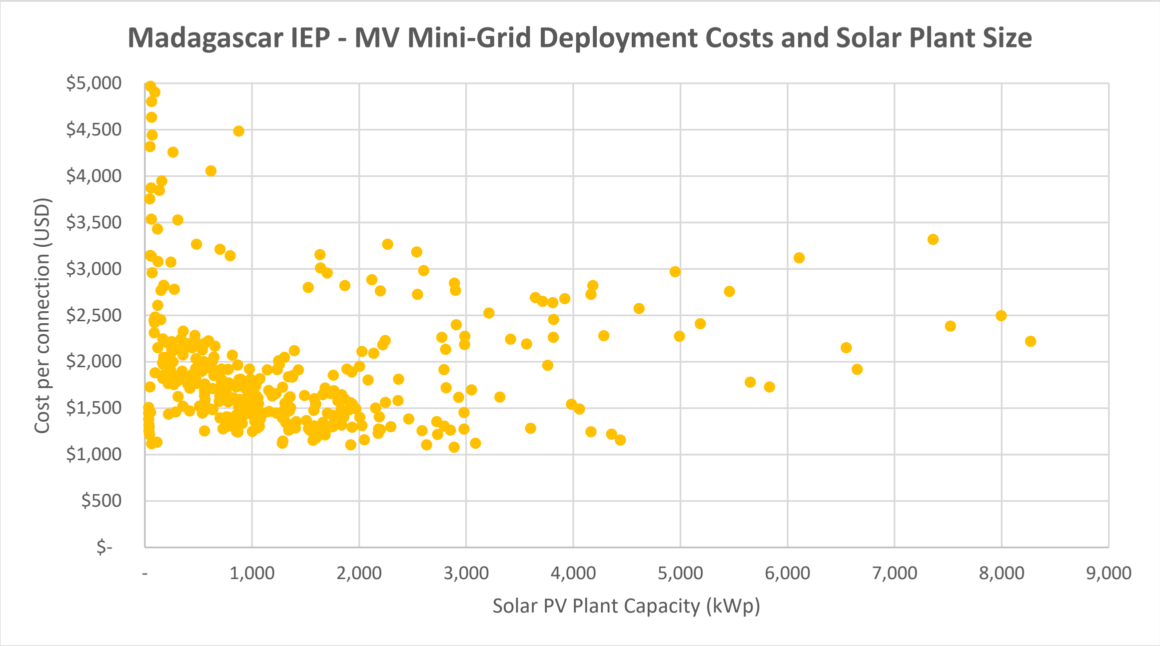


A review of the project size and cost for MV mini-grids in Madagascar reveals that MV mini-grids have slightly higher costs per connection, despite presenting with lower unit costs than LV mini-grids. This is attributable to the costs of transformers and the higher-cost of MV construction compared to LV network costs. Analysis of MV mini-grid costs reveals that 99 percent of MV mini-grids result with costs below USD 2,000 per consumer that is generally regarded as the limit of viability for mini-grid development. Lot 3 mini-grids above the USD 2,000 per connection threshold are not viable based on traditional metrics and would likely require additional subsidies. Figure 23 illustrates the distribution of cost-versus-plant capacity for the population of 371 MV mini-grids evaluated in this analysis. The solar PV array size is generally proportional to evaluated peak demand based on the results of HOMER analysis performed for MV mini-grids. Communities with larger populations have higher demand and require larger solar power plants to supply reliable electricity. The cost per connection declines with increasing solar plant size. However, for PV plant sizes above 5 MW, some of these MV mini-grid candidates have large service territories and the relative impact of MV infrastructure costs begins to outweigh the economies of scale in having larger MV networks.

Compared to other countries with low rural electrification rates, the sheer volume of MV mini-grids and their size both in terms of connections and MWp capacity are notable. This is because many of the MV mini-grids, and indeed some of the largest ones, are grid-edge mini-grids in peri-urban areas. In other countries, these large grid-edge systems could be incorporated into the national grid, but JIRAMA's relatively small coverage area results in technically constrained grid expansion potential.

The majority of unelectrified communities in Madagascar are beyond the immediate reach of JIRAMA and existing private mini-grid service providers. For all of these communities, an evaluation of off-grid service options was conducted, including the option of forming mini-grids powered by hydroelectric resources. Further details are provided in Annex C1 - Hydropower potential for unelectrified Madagascar.

Figure 23. MV mini-grid distribution of size and projected costs



LV Mini-grids

For rural communities where consumers reside within a 600-meter radius, customers can be served by a small mini-grid power plant and LV distribution network. Figure 24 presents mini-grid sites identified with clusters of at least 100 housing structures that are beyond the limits of near-term grid expansion and not suitable for clustering into larger MV mini-grids. The penetration rates used to evaluate these mini-grids assumed 25 percent of all consumers would connect in the first year of operation, reaching 100 percent by 2030. Annex A3 provides a list of the mini-grid projects.

Figure 24. LV mini-grids throughout Madagascar, including detailed view of an example in Maevatanana district, Betsiboka region

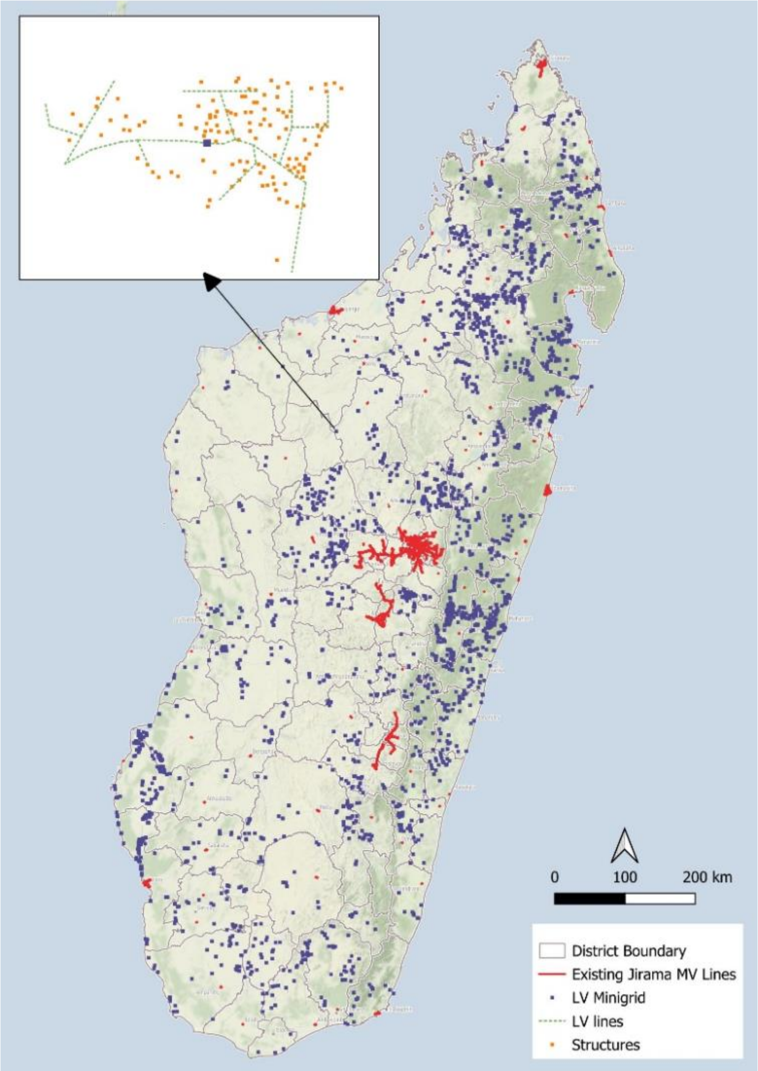
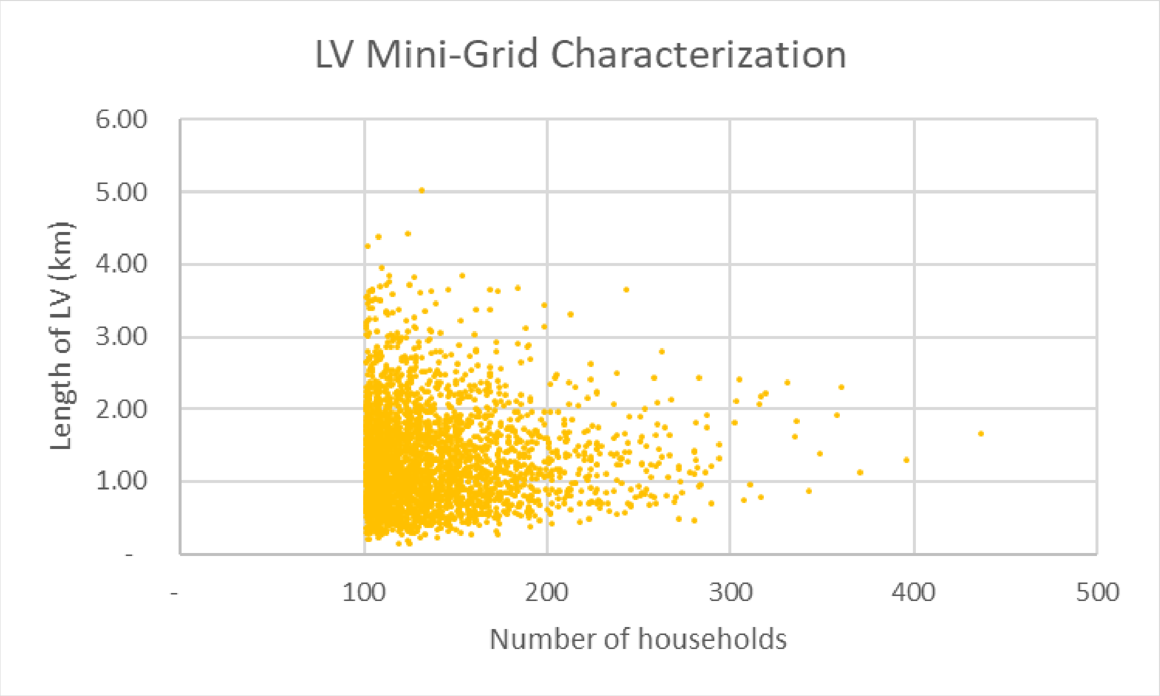


Figure 25 illustrates the relationship of the number of households served in relation to the size (length) of the LV distribution network. The graph includes 2,852 LV mini-grid sites that were evaluated. The sites vary widely by population density, and there is no clear trend line to indicate that more populous communities require more LV infrastructure. In fact, the LV mini-grid candidate with the greatest number of households (437 households) requires less than 2 km of LV network, while the mini-grid that requires the largest LV network (approximately 5 km) will serve just 132 households. In these circumstances, where projects fall between the margins of a specific electrification modality, a mini-grid developer might consider a hybrid approach wherein a mini-grid serves the main commercial hub and standalone solar for the more remote energy consumers to decrease LV length. Overall, the LV mini-grid sites have a median size of 126 households, so many sites are very close to the 100-household cutoff.

Figure 25. **LV mini-grid characteristics illustrating number of households versus length of LV network**



To maximize near-term electrification progress, the LV mini-grid sites were evaluated to determine overall cost effectiveness and LCOE to guide the prioritization process of the large population of these mini-grids. These mini-grids have also been evaluated technically and financially, then ranked from lowest to highest cost per consumer served.

As was mentioned previously, there are over 100 existing mini-grids in Madagascar today. Many of these mini-grids have received capital subsidies through the Universal Energy Facility (UEF), a fund managed by Sustainable Energy for All (SEforALL), or other donor programmes. The capital subsidies in the UEF programme are distributed in the form of one-time results-based financing (RBF) payments to the mini-grid developers at a rate of USD 592[37] per verified consumer connection. Private mini-grid developers with operations in Madagascar are more likely to prioritize near-term construction of mini-grids that would qualify for UEF or similar co-financing. Mini-grid developers will be able to discern the most advantageous sites by querying the IEP database and geospatial platform to inform their investment decisions.

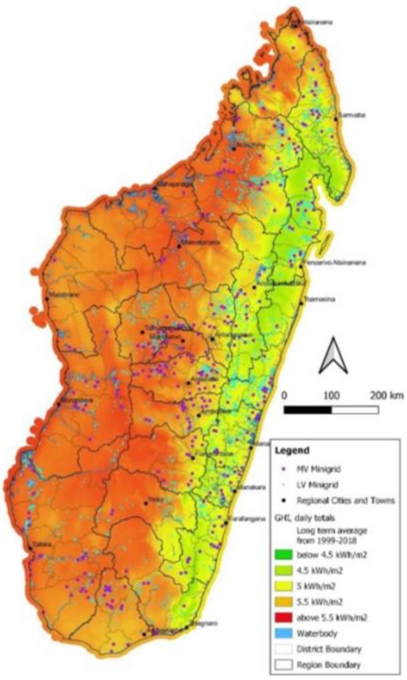
The entire database of 2,852 LV mini-grid candidates has the potential to provide service to approximately 470,000 Malagasy households, businesses and public institutions by 2030, representing over 5 percent of the universal electrification target. If the mini-grids are developed, they will most likely be financed and implemented by private-sector developers licensed by ADER and partially funded by either the UEF or other parallel or successor donor programmes.

The generation plants for the LV mini-grids were dimensioned to serve projected consumption in 2030 as projected by population growth and annual load projections for each community. The base case scenario assumes that the LV mini-grids will achieve 100 percent renewable fraction

[37] More details of the UEF programme rules and qualification criteria can be found on the SEforALL website. Information in this report is current as of August 2023. https://www.seforall.org/UEF-mini-grids

with solar PV arrays and battery storage, but without any diesel generation plants. As discussed in the methodology section, three models were defined to evaluate mini-grid characteristics, the first for the median mini-grid site that will serve 132 consumers; the second for the mini-grid designed for 160 consumers, representing the upper quartile of the LV mini-grid project database; and the largest mini-grid site of the 2,852 LV mini-grids, which comprises 437 connections. The load for each of these three mini-grid archetypes was specified for multiple geographic areas to optimize the generation infrastructure sizing and investment and other characteristics shown in Table 15. The Madagascar IEP mini-grid locations are overlaid with solar resource characteristics; global horizontal irradiation (GHI) in kWh per square meter per day for Madagascar in relation to the location of the proposed mini-grid sites (MV and LV). [38] is shown in Figure 26.

Figure 26. GHI with proposed mini-grids
(Source for GHI : ESMAP SOLARGIS 2023).



The mini-grids were evaluated in hybrid configuration with diesel generation, and then evaluated as renewable-only generation mini-grids. In most cases, the optimal renewable energy fraction was between 91 percent and 94 percent. In the renewable-only modelling run, diesel generation was eliminated in the HOMER models. This methodology revealed that LV mini-grids can be fully renewable at cost parity with hybrid mini-grids, but the elimination of fossil fuel generation results in an annual capacity shortage (constrained operating reserves) between 7.5 percent and 8.1 percent and a total unmet electricity load of between 3.8 percent and 4.5 percent. Under this scenario, the private mini-grid operators would need to adjust their tariffs and revenue forecasts to anticipate this unmet load in their financial models. The overall loss of revenue associated with unmet load could be partially mitigated by load shifting attributable to customer incentives such as time of use (TOU) tariffs, demand charges, demand-

[38] https://solargis.com/maps-and-gis-data/download/madagascar

side management, or other voluntary programmes. Nevertheless, it is likely that deliberately undersizing mini-grids for cost effectiveness in a fully renewable scenario will negatively impact grid reliability compared to mini-grids with backup generation.

LV mini-grid characteristics are presented by district in Table 15.

Table 15. LV mini-grids by district

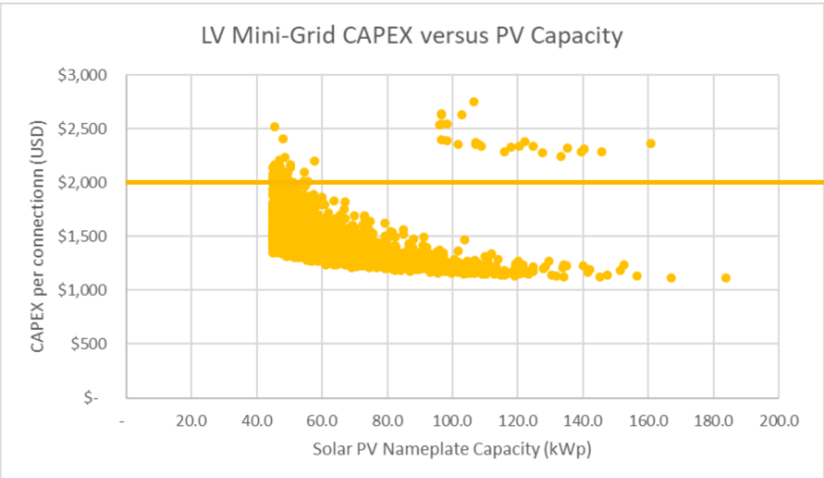
District Name	LV Mini-Grids by 2030	LV Mini-Grid Connections (2030)	Total PV Array Capacity (kWp)	Average Cost /consumer (USD)
Ambalavao	28	4,208	1,565	1,559
Ambanja	58	10,305	3,798	1,357
Ambato Boeni	19	2,916	1,083	1,455
Ambatofinandrahana	23	3,816	1,411	1,447
Ambatolampy	4	529	199	1,778
Ambatomainty	2	268	100	1,567
Ambatondrazaka	47	7,104	3,108	1,613
Ambilobe	21	3,881	1,427	1,429
Amboasary-Atsimo	48	7,072	2,635	1,445
Ambositra	15	2,077	776	1,715
Ambovombe-Androy	18	2,375	891	1,629
Ampanihy Ouest	38	5,481	2,045	1,628
Amparafaravola	30	4,848	1,794	1,416
Analalava	17	2,844	1,051	1,463
Andapa	27	5,314	1,948	1,369
Andilamena	27	5,237	1,922	1,350
Anjozorobe	81	12,166	4,525	1,502
Ankazoabo	3	427	160	1,351
Ankazobe	19	3,073	1,138	1,464
Anosibe-An'ala	36	6,197	2,287	1,506
Antalaha	13	1,933	720	1,434
Antanambao Manampontsy	14	2,773	1,017	1,405
Antanifotsy	59	9,606	3,556	1,474
Antsalova	9	1,277	477	1,479
Antsohihy	49	7,498	2,786	1,415
Bealanana	79	14,136	5,409	1,462
Befandriana Nord	132	23,170	8,541	1,398
Befotaka	9	1,408	523	1,425
Bekily	22	2,864	1,076	1,641
Belo Sur Tsiribihina	15	2,130	796	1,479
Beloha	3	453	168	1,479
Benenitra	17	2,830	1,046	1,365
Beroroha	18	3,126	1,153	1,327
Besalampy	6	881	328	1,496
Betioky Atsimo	31	4,809	1,851	1,431

Betroka	10	1,280	481	1,560
Brickaville	25	3,862	1,434	1,530
Fandriana	4	555	264	1,963
Farafangana	8	1,255	465	1,557
Fenerive Est	50	8,418	3,111	1,437
Fenoarivobe	89	13,701	5,151	1,436
Iakora	9	1,423	528	1,423
Ifanadiana	28	4,531	1,679	1,539
Ihosy	74	12,796	4,724	1,390
Ikalamavony	16	2,477	920	1,452
Ikongo	13	1,947	725	1,663
Ivohibe	12	2,151	792	1,349
Maevatanana	34	5,086	1,892	1,406
Mahabo	33	4,694	1,907	1,541
Mahanoro	89	15,583	5,747	1,523
Maintirano	5	648	243	1,570
Mampikony	21	2,826	1,058	1,510
Manakara Atsimo	19	2,754	1,026	1,741
Mananara-Avaratra	85	14,789	5,457	1,379
Manandriana	8	1,284	477	1,493
Mananjary	45	7,424	2,747	1,526
Mandoto	14	1,999	745	1,526
Mandritsara	138	23,129	8,551	1,377
Manja	49	8,540	3,150	1,364
Maroantsetra	11	1,629	606	1,418
Marolambo	79	14,878	5,468	1,501
Marovoay	7	1,155	427	1,497
Miandrivazo	33	5,043	2,065	1,487
Mitsinjo	3	414	155	1,564
Moramanga	50	7,570	2,814	1,527
Morombe	86	13,716	5,201	1,443
Morondava	14	2,335	863	1,430
Nosy-Varika	29	4,374	1,627	1,594
Port-Berge (Boriziny-Vaovao)	53	8,206	3,046	1,459
Sainte Marie	1	159	59	1,365
Sakaraha	26	4,009	1,489	1,412
Sambava	90	15,793	5,824	1,342
Soalala	2	280	105	1,677
Soanierana Ivongo	30	5,052	1,867	1,402
Taolagnaro	19	2,896	1,076	1,461
Toliary-II	123	22,392	8,433	1,407
Tsaratanana	1	132	50	1,616
Tsihombe	4	549	205	1,680
Tsiroanomandidy	119	18,876	6,998	1,453

Vangaindrano	11	2,129	781	1,479
Vatomandry	42	7,052	2,606	1,421
Vavatenina	6	933	346	1,433
Vohemar	66	11,423	4,217	1,387
Vohipeno	4	623	317	1,891
Vondrozo	28	4,355	1,616	1,533
Grand Total	**2852**	**468,159**	**174,846**	**1,455**

The 2,852 LV mini-grids in the geospatial database exhibit clear trends. As the number of consumers increases, demand and power plant capacity increase proportionally. Mini-grids that serve larger communities with larger PV arrays and battery storage result in lower cost per connected consumer as illustrated in Figure 27. Note that there are significant variances from this trend as illustrated with outliers that have surprisingly higher costs than the majority of LV mini-grids in this database. The higher costs for the outliers result from higher-than-average distribution network costs attributable to more dispersed population in these communities. In these outlier communities, the costs per connection could be reduced by considering a hybrid approach that allows standalone solar systems (SSS) to be implemented on the outskirts of the mini-grid to economize the LV distribution network. Alternately, the outlier connections can be served by so-called "mesh grids" which are networks of interconnected SSS with the ability to share solar and battery capacity between multiple connected structures. Mesh grids were not explicitly modelled in the analysis but could be subject to further analysis.

Figure 27. LV mini-grid characteristics



Note: the US$2000 per connection cutoff is assigned to distribution costs only. Adding generation costs takes the total cost over the threshold in systems that are low density with fewer connections.

As illustrated in the MV mini-grid analysis, the LV mini-grid population was also organized from lower to higher cost for purposes of projecting deployment timetable. The deployment criteria for the LV mini-grid population are as follows:

Lot 1: Current UEF incentives of USD 592 per connection account for > 50% of CAPEX. To be constructed 2024–2027. There are 58 Lot 1 mini-grids representing 18,519 connections in 2030 for an average of 319 connections per mini-grid.

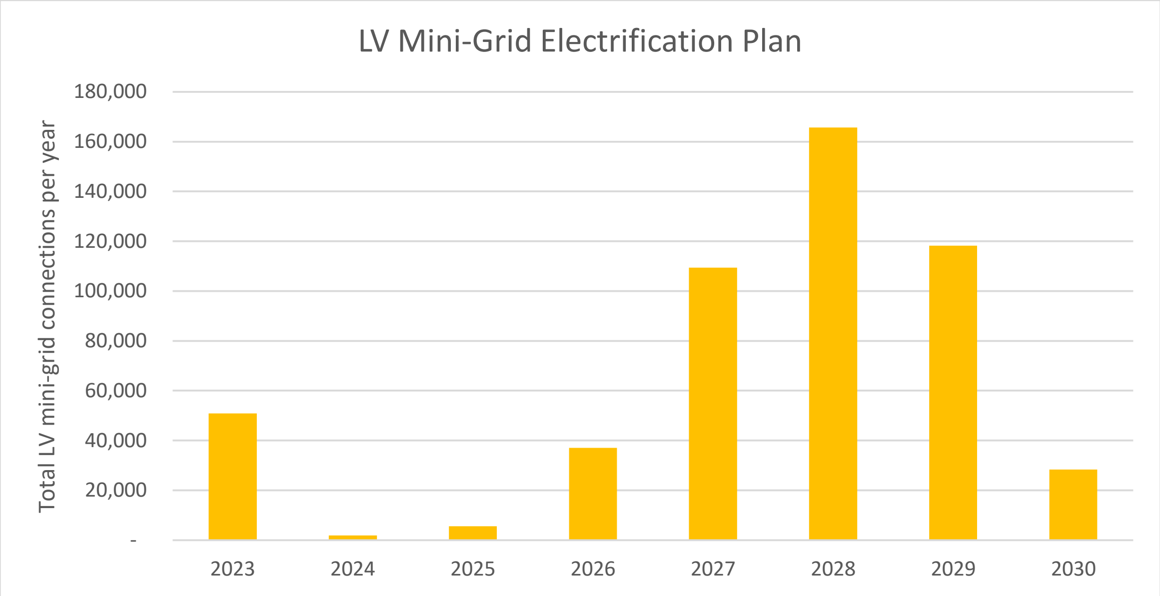
Lot 2: Current UEF incentives of USD 592 per connection account for between 40 and 50 percent of CAPEX. To be constructed 2026–2029. There are 1,774 Lot 2 mini-grids representing 308,147 connections in 2030 for an average of 174 connections per mini-grid.

Lot 3: Current UEF incentives of USD 592 per connection account for less than 40 percent of CAPEX. To be constructed 2027–2030. There are 1,020 Lot 3 mini-grids representing 141,493 connections in 2030 for an average of 139 connections per mini-grid.

It should be noted that the UEF is only one among many funding sources that may offer similar RBF structures to mini-grid developers during the electrification campaign. Nevertheless, the UEF RBF programme offers an illustrative example for the subsidy levels that are generally acceptable to private-sector investors and regarded as viable in the 2023 Malagasy mini-grid sector. The rationale for determining the lot thresholds in terms of the UEF cost share is to characterize LV mini-grid investments with respect to terms that are likely to interest and attract mini-grid developers. Given that capital subsidies are generally limited to no more than 50 percent of total project costs, Lot 1 projects are likely to be financially viable today. Mini-grid developers look to blend capital resources including grants, debt and equity. Grant financing to the order of 40 percent of total project cost offers a reasonable threshold for Lot 2 that is often considered the level necessary to attract mini-grid investment in many mini-grid markets. The projects in Lot 3 represent viable mini-grids that are not attractive in today's market unless costs come down or ADER and GoM are able to define improved subsidy funding for these LV mini-grid candidates.

A summary of the proposed LV mini-grid deployment by year is presented in Figure 28. The most aggressive years of the programme are 2027–2029 when Lot 2 is underway. Based on discussions with ADER and existing records of the mini-grid sector in Madagascar, there are believed to be 50,882 connections to mini-grids at the time of this report. Since ADER doesn't have these demographics disaggregated by MV or LV mini-grids, all existing mini-grid customers are included in the 2023 figures for LV mini-grids. Therefore, the electrification efforts to be financed and planned under the IEP begin with the data in 2024, as presented in Figure 28.

Figure 28. Implementation of LV mini-grids



Standalone solar solutions

In this report, off-grid solar service has been considered the most pragmatic electrification option where the cost of grid expansion exceeds USD 1,250 per connection and in areas where the population density is too low to support mini-grid development (meaning clusters of potential consumers are fewer than 100 in a 600-meter radius and the distribution cost component of mini-grid electrification exceeds USD 2,000 per connection). The resulting market is very large and covers most of rural Madagascar. Based on the results of the IEP analysis, the standalone solar option can be characterized as the electrification modality of last resort; the connections in this category include all structures that didn't meet electrification criteria for all other modalities. As a result, the SSS electrification candidates are widespread throughout Madagascar with at least one standalone solar system target customer in each of the country's 119 districts. The total number of standalone solar systems to be deployed by 2030 is 5,713,204, comprising 52 percent of all electricity consumers in 2030, more than double the contribution of any other modality.

A map of solar standalone solutions for universal electrification by 2030 is presented in Figure 29. This figure presents a "heat map" using darker colours to illustrate higher density of standalone solar deployment.

Figure 29. Standalone solar heatmap

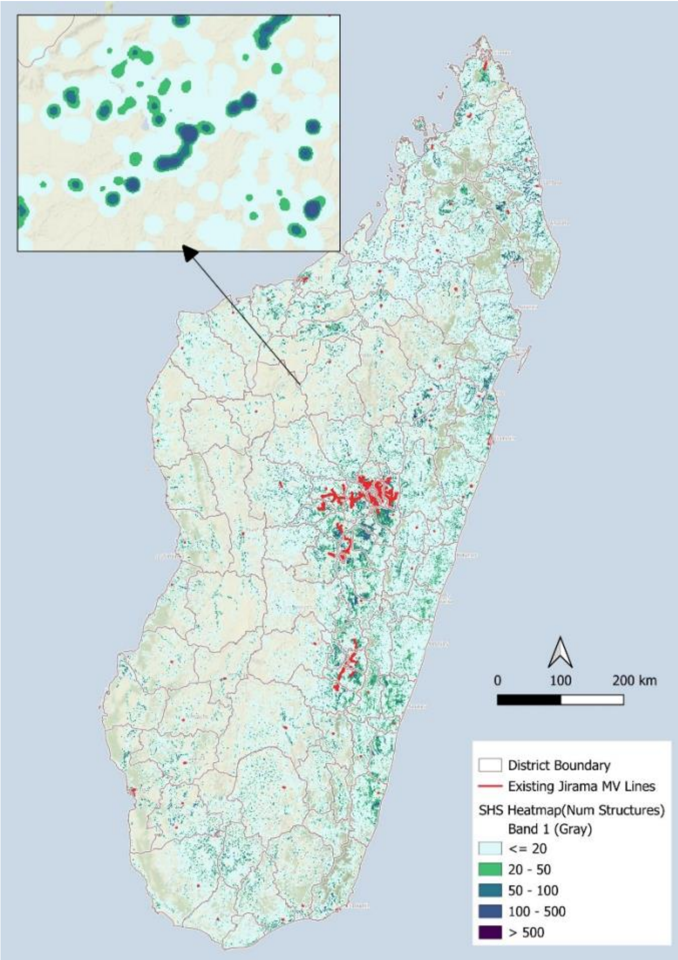


Table 16 presents standalone solar service expansion requirements to meet full access by 2030. The deployment schedule represents the rate of deployment needed to achieve universal access by 2030. This is not a reflection of local private sector capabilities, which are likely to be much more modest than the rate of sales required. While the World Bank supported Least-Cost Electricity Access Development (LEAD) project is being reorganized to deploy one million standalone solar systems, it is the only known significant programme of its kind. There are likely to be significant obstacles to universal access based on sales levels and affordability hurdles in rural areas that have not yet been addressed. These challenges include financial incentives that are not yet in place to fully incentivize solar PV service providers; challenge grants that have not yet been implemented to encourage service providers to move into more challenging remote areas; and the absence of consumer-facing subsidies that will very likely be needed for lower-income families and businesses in rural and remote areas of Madagascar.

Additionally, the tier 2 electrification costs are appropriate for residential consumption in remote areas but could be insufficient for rural small and medium enterprises (SMEs) or productive use of electricity (PUE) in rural areas. As the SSS programme proceeds, a more detailed assessment of electrification needs in these areas could help to inform a blend of tiers 2 and 3 SSS. Nevertheless, based on primary data collection, consumers in these areas are 99 percent residential, so it is reasonable to approximate the SSS plan as 100 percent tier 2 until more granular assessment is conducted. Large-scale growth in sales of solar standalone solutions will need to address two principal issues. These include first-time sales to households that have not yet purchased solar products and therefore, resistance will need to be overcome to engage this market segment. In addition, given that solar PV systems have useful livespans of three to five years, it will be necessary to replace aging solar PV systems in order to continue to grow toward universal access by 2030 without attrition. For this reason, the solar standalone deployment model includes system replacement in the fifth year of service.

Figure 30. Implementation schedule requirements for solar standalone solutions by year through 2030

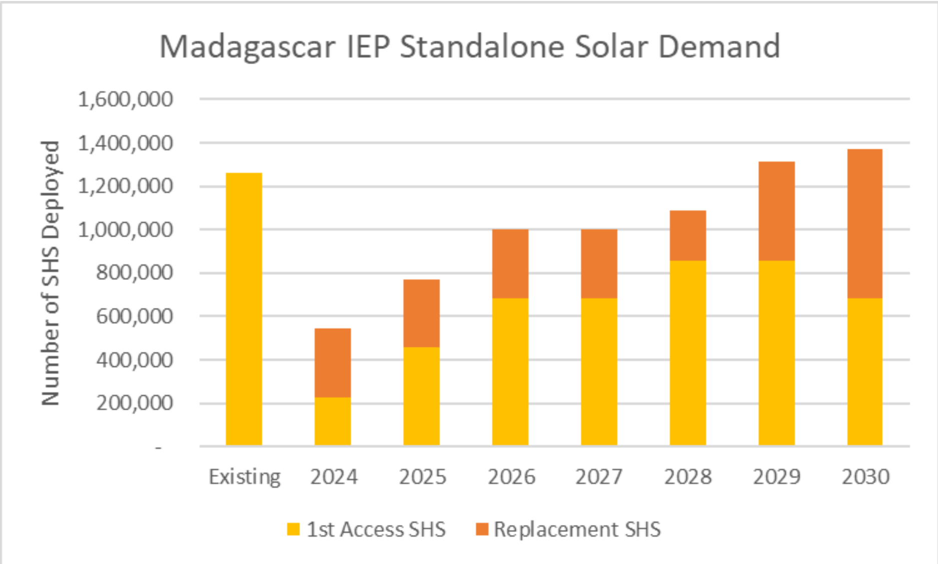


Table 16. Solar standalone solutions by region

Region	District	SSS Demand
Alaotra Mangoro	Ambatondrazaka	64164
Alaotra Mangoro	Amparafaravola	90216
Alaotra Mangoro	Andilamena	28098
Alaotra Mangoro	Anosibe-An'ala	37404
Alaotra Mangoro	Moramanga	90146
Amoron I Mania	Ambatofinandrahana	37675
Amoron I Mania	Ambositra	71683
Amoron I Mania	Fandriana	42864
Amoron I Mania	Manandriana	21669
Analamanga	1er Arrondissement	10893
Analamanga	2e Arrondissement	8703
Analamanga	3e Arrondissement	4732
Analamanga	4e Arrondissement	10480
Analamanga	5e Arrondissement	6906
Analamanga	6e Arrondissement	203
Analamanga	Ambohidratrimo	26104
Analamanga	Andramasina	63302
Analamanga	Anjozorobe	42723
Analamanga	Ankazobe	60314

Analamanga	Antananarivo Atsimondrano	52519
Analamanga	Antananarivo Avaradrano	13298
Analamanga	Manjakandriana	47356
Analanjirofo	Fenerive Est	77036
Analanjirofo	Mananara-Avaratra	69885
Analanjirofo	Maroantsetra	81135
Analanjirofo	Sainte Marie	4859
Analanjirofo	Soanierana Ivongo	56063
Analanjirofo	Vavatenina	57954
Androy	Ambovombe-Androy	72382
Androy	Bekily	77488
Androy	Beloha	24541
Androy	Tsihombe	13893
Anosy	Amboasary-Atsimo	51272
Anosy	Betroka	81924
Anosy	Taolagnaro	49902
Atsimo Andrefana	Ampanihy Ouest	93522
Atsimo Andrefana	Ankazoabo	26803
Atsimo Andrefana	Benenitra	16711
Atsimo Andrefana	Beroroha	23888
Atsimo Andrefana	Betioky Atsimo	80441
Atsimo Andrefana	Morombe	40231
Atsimo Andrefana	Sakaraha	54212
Atsimo Andrefana	Toliary-I	1467
Atsimo Andrefana	Toliary-II	64648
Atsimo Atsinanana	Befotaka	15851
Atsimo Atsinanana	Farafangana	64438
Atsimo Atsinanana	Midongy-Atsimo	18271
Atsimo Atsinanana	Vangaindrano	81510
Atsimo Atsinanana	Vondrozo	40745
Atsinanana	Antanambao Manampontsy	14060
Atsinanana	Brickaville	62163
Atsinanana	Mahanoro	63693
Atsinanana	Marolambo	62470
Atsinanana	Toamasina I	340
Atsinanana	Toamasina II	78774
Atsinanana	Vatomandry	45586
Betsiboka	Kandreho	8988
Betsiboka	Maevatanana	46404
Betsiboka	Tsaratanana	46230
Boeny	Ambato Boeni	78531
Boeny	Mahajanga I	31
Boeny	Mahajanga II	46527
Boeny	Marovoay	52781

Boeny	Mitsinjo	50159
Boeny	Soalala	34006
Bongolava	Fenoarivobe	46266
Bongolava	Tsiroanomandidy	94447
Diana	Ambanja	64140
Diana	Ambilobe	85454
Diana	Antsiranana I	843
Diana	Antsiranana II	67079
Diana	Nosy-Be	39799
Fitovinany	Ikongo	64032
Fitovinany	Manakara Atsimo	73910
Fitovinany	Vohipeno	23464
Haute Matsiatra	Ambalavao	57117
Haute Matsiatra	Ambohimahasoa	43899
Haute Matsiatra	Fianarantsoa I	4260
Haute Matsiatra	Ikalamavony	31074
Haute Matsiatra	Isandra	39887
Haute Matsiatra	Lalangina	17692
Haute Matsiatra	Vohibato	45844
Ihorombe	Iakora	22586
Ihorombe	Ihosy	72057
Ihorombe	Ivohibe	27004
Itasy	Arivonimamo	54469
Itasy	Miarinarivo	32894
Itasy	Soavinandriana	48928
Melaky	Ambatomainty	13119
Melaky	Antsalova	22082
Melaky	Besalampy	51868
Melaky	Maintirano	30694
Melaky	Morafenobe	14175
Menabe	Belo Sur Tsiribihina	39998
Menabe	Mahabo	34843
Menabe	Manja	29525
Menabe	Miandrivazo	36767
Menabe	Morondava	27641
Sava	Andapa	84835
Sava	Antalaha	90481
Sava	Sambava	153989
Sava	Vohemar	117762
Sofia	Analalava	71510
Sofia	Antsohihy	48512
Sofia	Bealanana	74879
Sofia	Befandriana Nord	95537
Sofia	Mampikony	43805

Sofia	Mandritsara	81775
Sofia	Port-Berge (Boriziny-Vaovao)	78658
Vakinankaratra	Ambatolampy	61276
Vakinankaratra	Antanifotsy	88085
Vakinankaratra	Antsirabe I	2771
Vakinankaratra	Antsirabe II	66818
Vakinankaratra	Betafo	65896
Vakinankaratra	Faratsiho	54818
Vakinankaratra	Mandoto	22938
Votovavy	Ifanadiana	49854
Votovavy	Mananjary	73366
Votovavy	Nosy-Varika	64515
Total		**5,715,227**

Facilities Electrification Analysis

An essential element of the Integrated Energy Plan (IEP) is electrification of the education and healthcare facilities. The results of electrification modelling taken together with public facility locations, characteristics and needs were used to inform electrification solutions for the electrification of schools and healthcare facilities. Figures 31 and 32 illustrate healthcare facility locations and electrification solutions, while Figures 33 and 34 illustrate school locations and electrification solutions. Note that Figure 32 indicates the location of the Phase 1 LEAD (47) healthcare facilities that have already been implemented as well as the Phase 2 facilities that are still pending. The Madagascar IEP Cold Chain report provides a more detailed analysis of the energy requirements and standalone system sizing for the cold chain needs of the healthcare facilities. In the electrification analysis, these facilities were assumed to have tier 2 system with associated investment costs.

Figure 31. Healthcare facility electrification solutions by technology

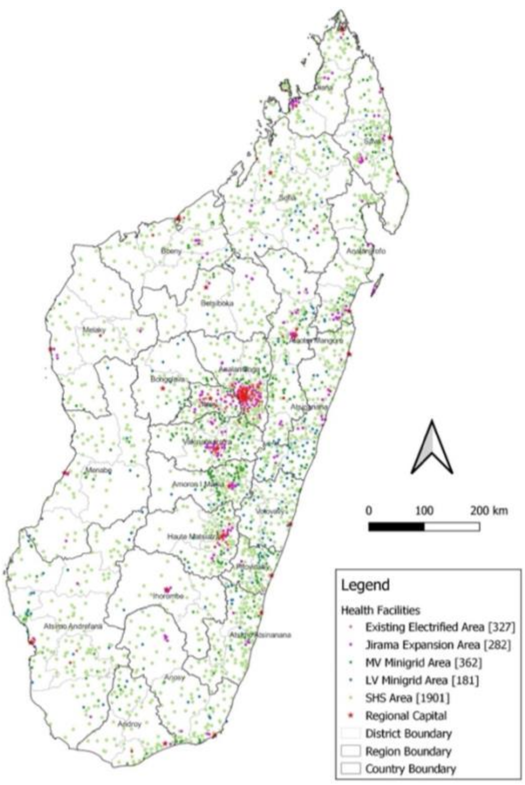


Figure 32. Healthcare facility locations in Madagascar (MoH 2023)

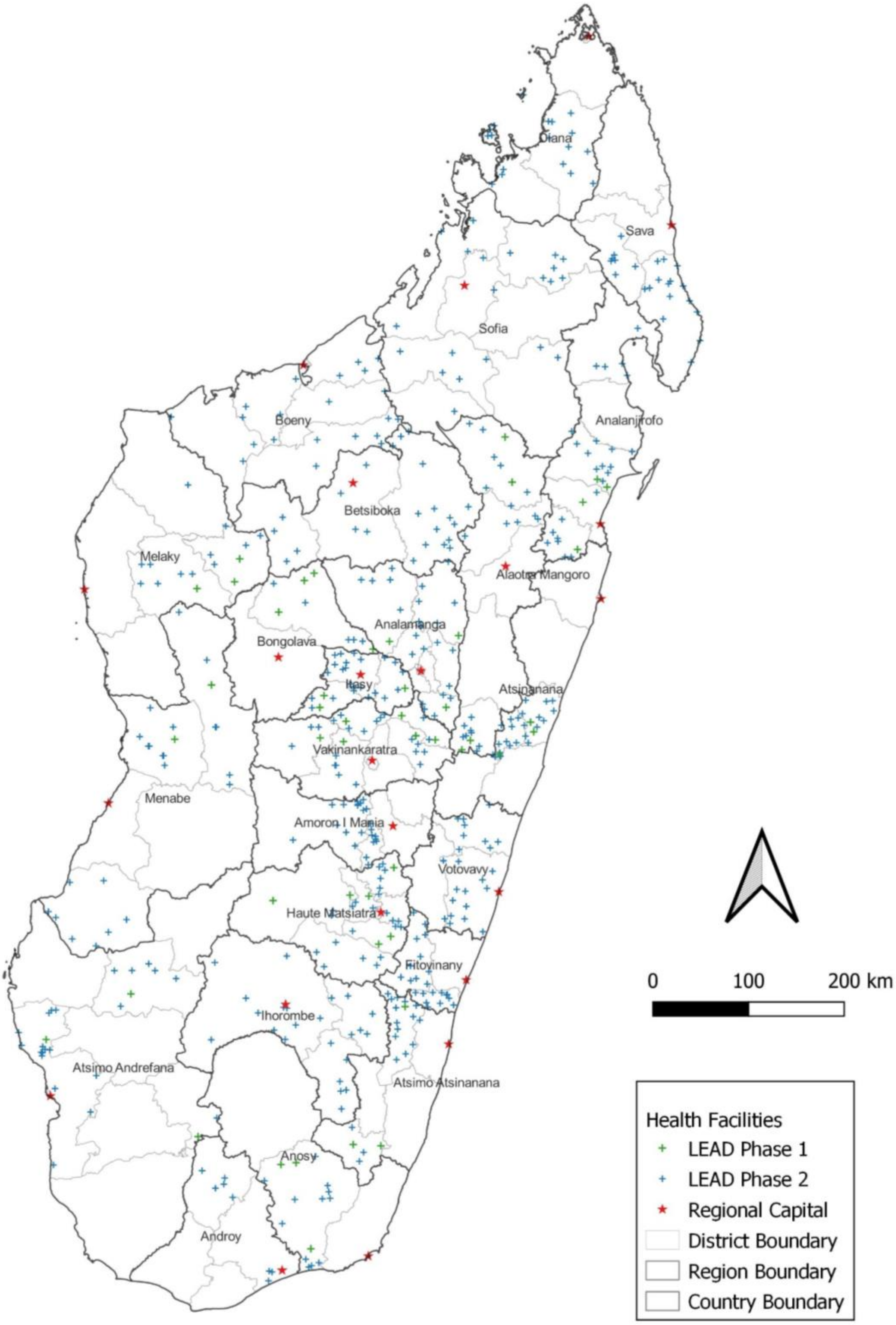


Figure 33. School locations in Madagascar (Source: OSM 2023)

These are opensource locations of all school types)

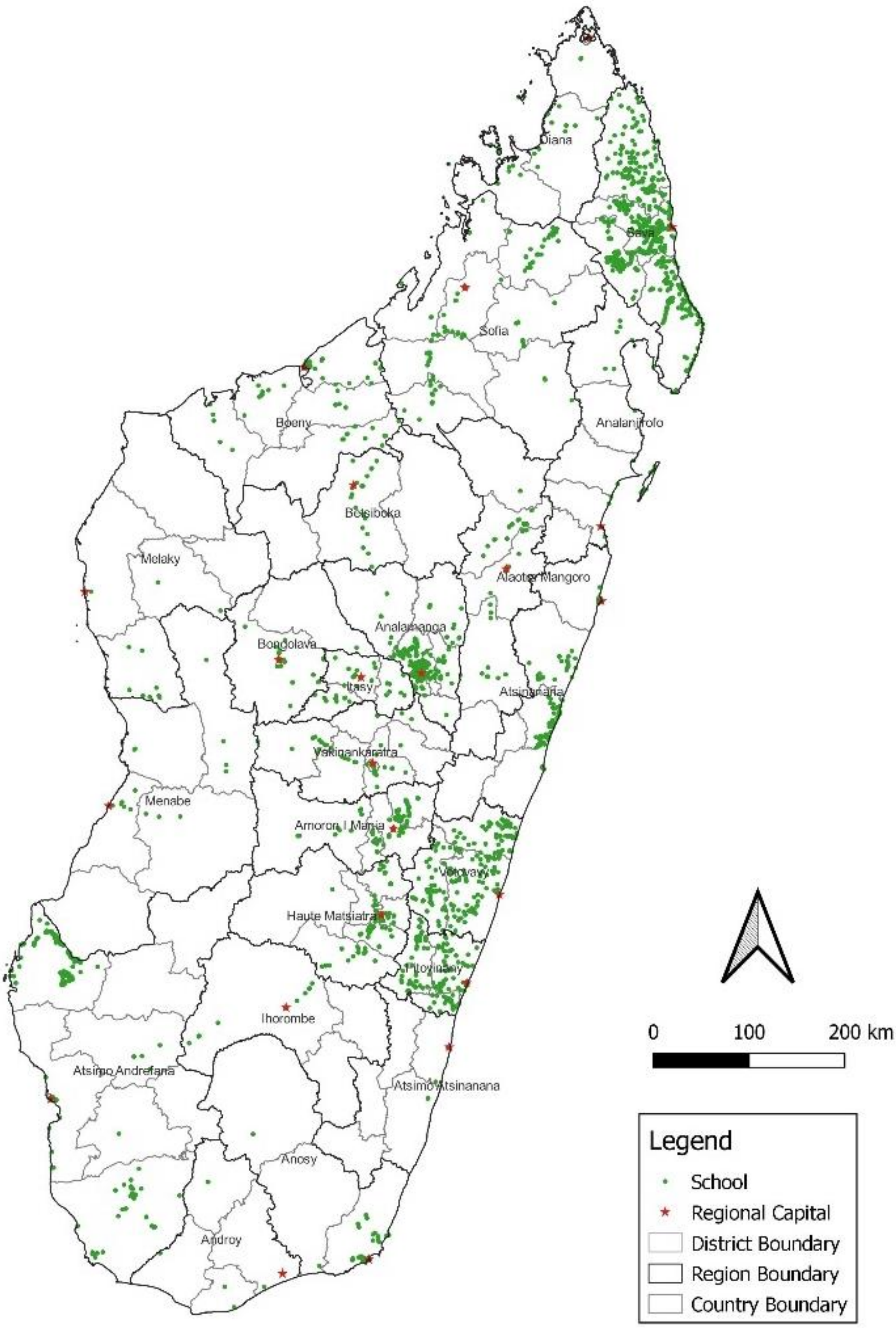
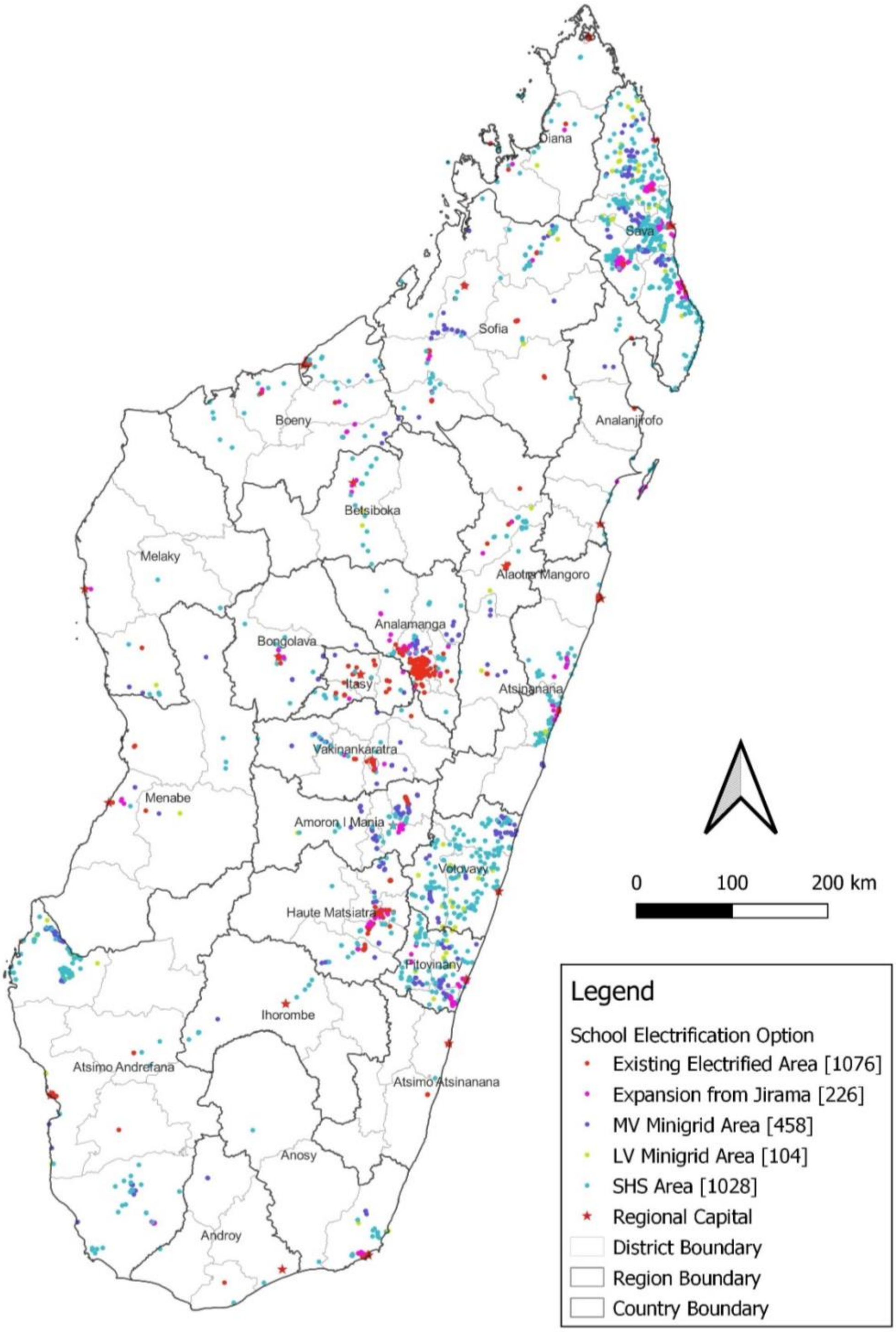


Figure 34. School electrification solutions by technology



ELECTRIFICATION IMPLEMENTATION AND FINANCING REQUIREMENTS

The IEP electrification plan will employ multiple electrification technologies to achieve universal access as described in previous sections of this report. This chapter describes the implementation of access expansion and the related financing requirements to achieve it. The presentation of access expansion follows two rates of universal access implementation, the first that seeks to achieve universal access by 2030, and the second that projects universal access by 2040.

Baseline case - Universal access by 2030

This section presents a summary of investment requirements and an implementation timeline that are required to achieve universal access by 2030, the baseline case for the Madagascar IEP. Recall that in the baseline case analysis, the model considers a minimum of tier 2 electrification based on the World Bank Energy Sector Management Assistance Program (ESMAP) Multi-Tier Framework (MTF) wherein universal access means 100 percent access to a modern source of electricity or lighting. Additionally, the baseline case scenario includes no improvements or hybridization to the existing JIRAMA isolated systems, but new mini-grids were considered with both medium voltage (MV) and low voltage (LV) distribution networks and renewable energy generation plants including solar or hydro with energy storage and no diesel generation.

Access Expansion

Table 17 presents a summary of access expansion by year and technology presented in the preceding section of this report. Note that achieving universal access includes 2022 JIRAMA consumers and an estimate of households and businesses that own and use solar standalone energy systems. In the case of JIRAMA consumers, the 2022 total (620,839) was used to estimate consumers in its existing service territory in 2023. Standalone solar consumers were estimated using results from the Madagascar MTF survey, which estimates solar use at 1.26 million (drawing from approximately 20 percent of households having some form of solar standalone system), although many of these systems are in areas with overlapping electrification modalities, for example standalone solar systems (SSS) in households that are already served by JIRAMA. Overall, by 2030, Madagascar will need to augment its existing electrification rate by adding 2.6 million customers (27 percent of the 2030 population) on the JIRAMA grids and 7.6 million off-grid customers (70 percent of the 2030 population).

Table 17. Rate of electrification implementation by technology to achieve universal access by 2030

Modality	2023	2024	2025	2026	2027	2028	2029	2030	Total	% of 2030 population
JIRAMA Existing Customers	620,839								620,839	6%
Densification	0	97,087	128,776	192,152	287,216	318,905	318,906	255,531	1,598,572	15%
Expansion	0	27,863	55,727	124,294	227,696	191,782	267,321	139,344	1,034,027	9%
MV Mini-Grids	0	-	54,938	217,250	413,187	428,003	249,384	72,256	1,435,019	13%
LV Mini-Grids	50882	1,852	5,556	37,111	109,371	165,707	118,227	28,299	517,004	5%
SSS	1,260,000	228,528	457,056	685,584	685,584	856,981	856,981	682,499	5,713,214	52%
Totals	1,931,721	355,330	702,052	1,256,391	1,723,055	1,961,377	1,810,818	1,177,929	10,918,675	100%

Figure 35. Share of electrification access in connections by technology

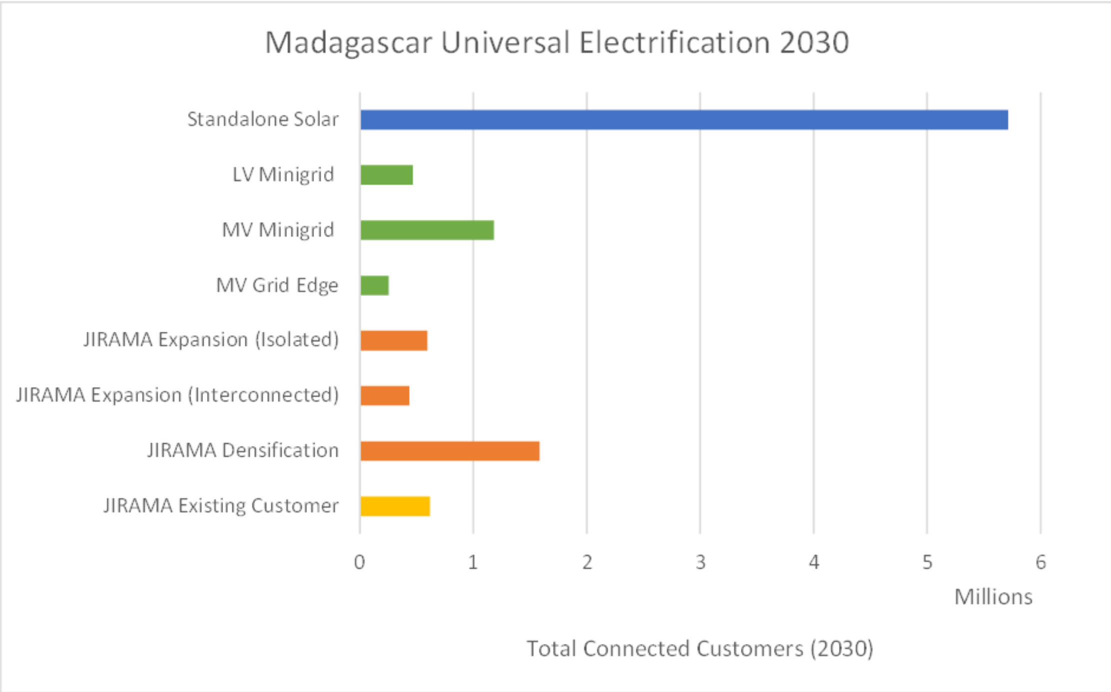


Figure 36. Summary of the IEP geospatial electrification analysis
(Source: IEP 2023)

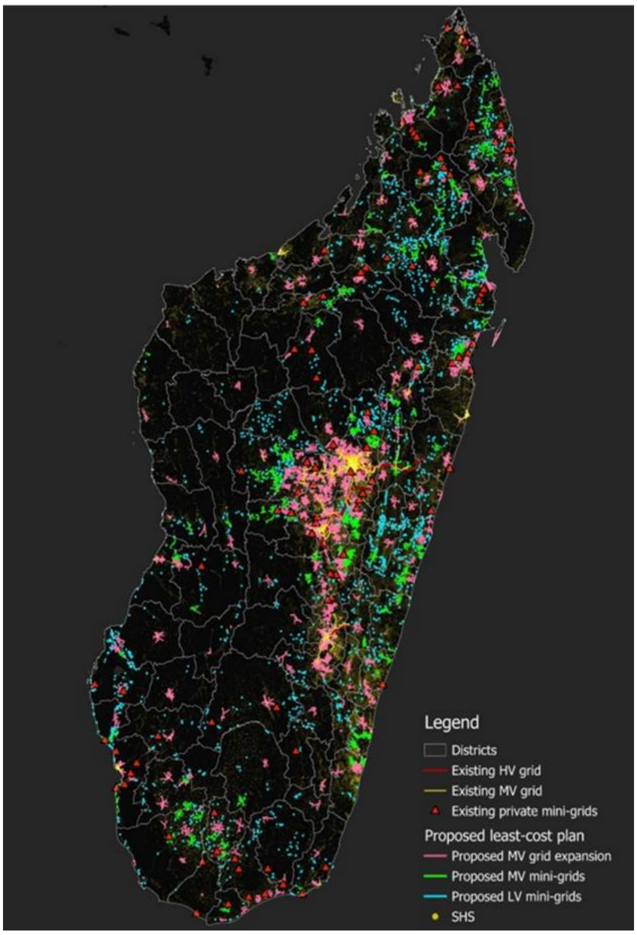
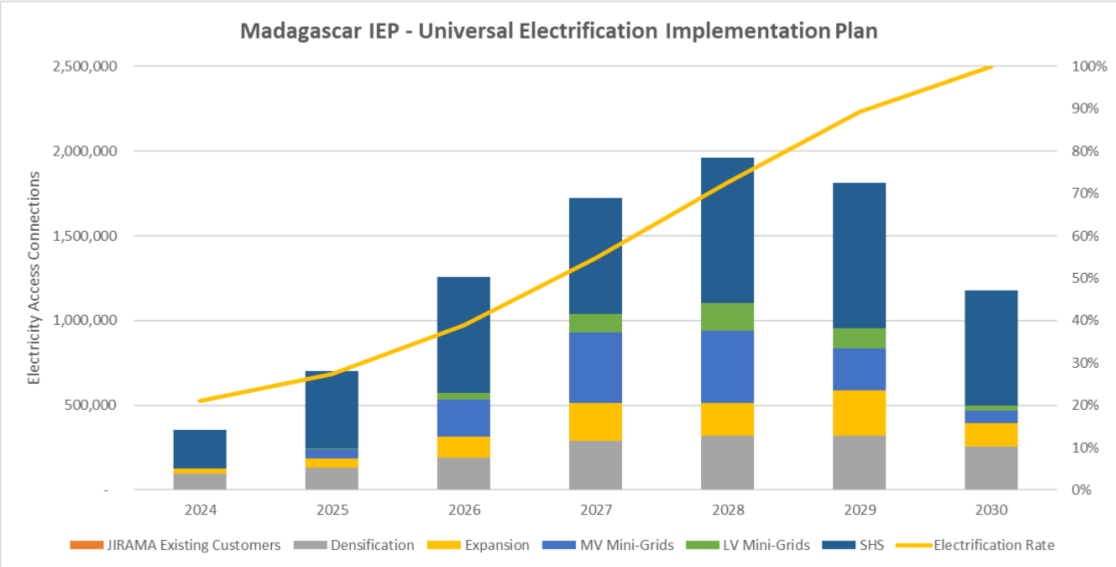


Figure 37 illustrates growth in service by electrification technology and presents new connections by year and cumulative growth in electrification access. Expansion of access grows slowly in the early years with momentum building in the later years to achieve universal access by 2030.

Figure 37. Electrification access implementation forecast with annual connections by technology and impact on electrification rate



Financing Requirements

This section presents an analysis of investment requirements that are tied to annual expansion targets and to growth of each electrification technology. Financing requirements will vary if the priorities are modified according to how projects are prioritized by national and local authorities, as well as by availability of financing available from the Government of Madagascar (GoM), development partners and private sector investment availability. Note that the CAPEX costs presented below are exclusive of VAT, however logistics costs are included.

Table 18. Financing requirements to achieve universal access by 2030

Electrification Modality	Total Future Connections	Total CAPEX	Cost per Connection (USD)	GoM Financing Requirements (USD)	Off-Grid Funding by Private Sector Developers (USD)	Connection Fees Paid by End-Use Consumer Grid & (USD)
Densification	1,598,572	$599,464,500	$375	$559,500,200	-	$39,964,300
Grid Expansion	1,034,027	$762,662,830	$738	$736,812,153	-	$25,850,677
MV Mini-Grids	1,435,019	$2,522,679,025	$1,758	$855,271,062	$1,631,532,500	$35,875,464
LV Mini-Grids	466,122	$667,221,243	$1,431	$277,808,605	$377,759,592	$11,653,046
Standalone Solar (SSS)	4,453,214	$1,558,624,896	$350	$801,578,518	$645,716,029	$111,330,350
SSS Replacement	2,628,074	$919,825,844	$350	$473,053,291	$381,070,707	$65,701,846
Total	**11,615,027**	**$7,030,478,338**		**$ 3,704,023,830**	**$ 3,036,078,827**	**$290,375,682**

The financing requirements presented in Table 18 are based on several assumptions. Since densification and grid expansion represent electrification investments to expand JIRAMA service, there is no role for private-sector investment. Consumers will be expected to contribute to project cost as a connection fee. Due to affordability limitations, the fee will not exceed USD 25. The threshold of USD 25 represents an equitable contribution from future electricity users that is not intended to unduly inhibit future connection targets.[39] All other costs are expected to be capitalized or financed through a supplemental government contribution to densification and grid expansion programme cost.

The mini-grid public sector contributions are assumed to follow the present Universal Energy Facility (UEF) co-financing rate of USD 592 per connected consumer allocated on the basis of results-based financing (RBF). This co-financing metric was applied to both MV and LV mini-grids in Table 18. This implies that the UEF and other mini-grid financing resources will be needed to finance more than USD1 billion by 2030. In addition, mini-grid developers will be able to secure and mobilize over USD 2 billion in investment capital to support the projected level of mini-grid expansion projected in Table 18.

Solar standalone investments are presented in two line items. The first shows investment costs for initial standalone solar systems that are installed by service providers at the outset of the programme. The second shows the replacement cost of aging solar solutions – standalone solar systems have an expected lifespan of five years, so replacement of these systems needs to be considered as a component of the IEP investment plan.

In all cases, the unit cost of standalone solar systems for the IEP is USD 350, which corresponds to a tier 2 system. The expectation is that the GoM will contribute the equivalent cost of a tier 1 system (USD 180) for each tier 2 standalone solar system installed. The balance of solar standalone financing would need to be financed by solar service providers at an estimated value of USD 646 million, with individual household consumers contributing an initial fee of USD 25 for a total of USD 111 million.

Given that the expected life of standalone solar systems is just five years, the investment includes a replacement requirement, which is shown in Table 13 in the line entitled, “SSS Replacement”. While GoM co-financing for replacement requirements will no doubt be difficult, it is almost certain that consumers will be unable to pay the full price of a replacement system. For this reason, the financing requirements for replacement costs use the same investment cost-sharing ratio as that used for initial standalone solar system installation. For these systems, it is unlikely that the GoM will be able to provide a significant capital subsidy, so they will need to be financed.

This financing plan is extremely aggressive when considering the pace of electrification in Madagascar thus far. It is unclear if there are adequate resources to manage the volume of grid and off-grid projects given the very significant level of grid and off-grid expansion that is needed. Capacity limitations (including implementation capacity and existing infrastructure capacity, among others) will need to be considered before finalizing the implementation and financing programme requirements.

[39] The private sector is however engaged in the payment of service connection fees to JIRAMA for grid electricity service and connection fees that will be paid mini-grid service providers. The fee structure for JIRAMA is published as a component of the JIRAMA tariff schedule but connection fees vary and mini-grid fees vary from provider to provider. For the Madagascar market initial connection fees are calculated at US$25 which is approximately 20 percent of the initial service drop cost per new connection.

Scenario 2 – Universal Access by 2040

This section presents the access implementation summary and financing requirements to meet universal access to electricity by 2040.

Access Expansion

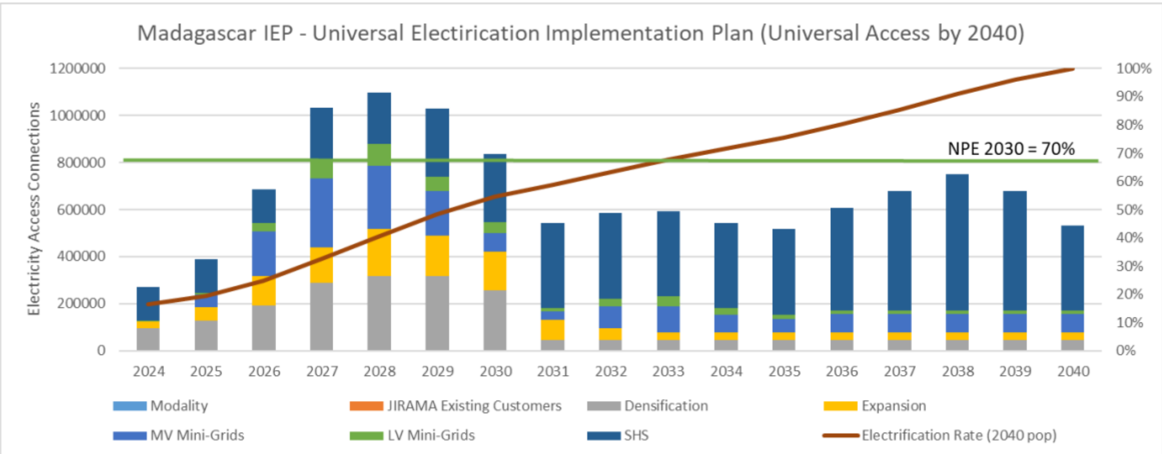
Table 19 presents a summary of access expansion including all electrification technologies presented in the baseline case electrification expansion analysis. Connection totals for each electrification technology show growth by programme year and cumulative totals through 2040.

Table 19. Rate of electrification implementation by technology to achieve universal access by 2040

Modality	2023	2024	2025	2030	2035	2040	Total	% of total
JIRAMA Existing Customers	620,839	0	0	0	0	0	620,394	5%
Densification	0	95,053	126,738	253,475	42,401	42,401	2,008,234	15%
Expansion	0	27,863	55,727	165,563	34,569	34,569	1,310,578	10%
MV Mini-Grids	0	-	54,938	78,653	54,192	76,917	1,819,604	14%
LV Mini-Grids	50,882	1,852	4,630	46,222	21,224	15,188	593,317	4%
SSS	1,260,000	144,847	144,847	289,694	362,117	362,117	6,909,028	52%
Totals	**1,931,721**	**269,615**	**386,879**	**833,607**	**514,504**	**531,193**	**13,261,600**	**100%**

The universal access by 2040 scenario is designed to mirror the GoM national electrification target. This scenario is designed to achieve 70 percent electrification by 2030, progressing to 100 percent by 2040. The growth trajectory is illustrated in Figure 38.

Figure 38. Electrification access implementation forecast with annual connections by technology and impact on electrification rate (2040 universal access scenario)



In the case of densification, the new connections can be added to existing JIRAMA networks at low cost and can be accomplished easily and effectively, provided that JIRAMA continues to maintain and expand its generation and transmission assets. In the 2040 scenario, JIRAMA could complete densification activities as early as 2030. Grid expansion will likely proceed more slowly given that it takes time to build capacity in country to mobilize multiple construction contractors to build out MV expansion projects, to establish supply chains needed to support ongoing expansion activities. Rather than assuming the grid expansion project packages can be completed in four-year increments, implementation has been extended to five years for these projects.

Mini-grid expansion will likewise be extended for a longer period to allow mini-grid developers to raise capital for lots 1 and 2. Lot 3, which includes the more expensive projects will not be implemented until after 2030 recognizing that it will take longer to raise the capital required for these higher-cost projects.[40]

Standalone solar solutions were significantly impacted by extending the electrification programme from a 2030 completion date to 2040. The 10-year extension allows for a much more gradual expansion of solar sales and additional time for service providers to extend service to more remote areas of Madagascar. It is also important to recognize that the longer implementation period will require a significantly higher level of standalone solar system replacements and a much higher programme cost. These costs have been included in the financing requirements shown in Table 20.

Lastly, extending the implementation period by 10 years will allow for expansion of grid resources as well as interconnection of maturing mini-grids with adjacent communities. Without knowing which of the larger mini-grids will be implemented early and whether the mini-grid operators will be able to raise the capital needed to expand service coverage, it is too soon to include these projections in the geospatial model. For clarity, households that were designated for grid electrification, mini-grid electrification and solar standalone service continue to be allocated to each of these electrification technologies in the 2040 scenario.

Financing Requirements

A summary of investment requirements by modality is presented in Table 20. To complete the financing analysis, the team assumed expansion activities were reprogrammed over a longer implementation period, and the effects of population growth were considered to address investment requirements. The primary factor that influenced financing requirements was the need to achieve full access by 2040, taking into account current levels of electrification and population growth. Investment requirements vary by modality as illustrated in Table 20. Note that the CAPEX costs presented below are exclusive of VAT, however logistics costs are included.

[40] Note that this analysis does not consider any replacement costs of mini-grid components in this timeframe.

Table 20. Financing requirements to achieve universal access by 2040

Electrification Modality	Total Connections	Total CAPEX	Cost per Connection (USD)	GoM Financing Requirements (USD)	Off-Grid Funding by Private Sector Developers (USD)	Connection Fees Paid by End-Use Consumer Grid & (USD)
Densification	2,008,234	$753,087,615	$375	$702,881,774	-	$50,205,841
Grid Expansion	1,310,578	$966,789,994	$738	$934,025,536	-	$32,764,459
MV Mini-Grids	1,819,604	$3,197,875,580	$1,757	$1,084,484,137	$2,067,901,337	$45,490,106
LV Mini-Grids	542,435	$845,803,409	$1,559	$323,290,995	$508,951,550	$13,560,864
Standalone Solar (SSS)	5,649,028	$1,977,159,763	$350	$1,016,825,021	$819,109,045	$141,225,697
SSS Replacement	9,713,052	$3,399,568,071	$350	$1,748,349,294	$1,408,392,487	$242,826,291
Total	**21,042,930**	**$11,140,284,432**		**$5,809,856,755**	**$4,804,354,418**	**$526,073,258**

SENSITIVITY ANALYSIS

The sensitivity analysis section will be drafted once the scenarios are complete and validated by SEforALL. The discussion below presents the methodology used.

Sensitivities to the electrification analysis

The following sensitivity analyses are proposed for electrification and will be applied to the baseline case:

Consider a 15 percent increase/decrease to the consumption values in kWh/month/consumer for the consumer categories analyzed

Projecting household, small commercial and public facility consumption for unelectrified communities requires carefully designed and implemented community surveys that can yield accurate results. However, the very nature of conducting community surveys gives rise to uncertainties that should be considered in electrification planning on a national scale. In addition to evaluating residential, commercial and public facility energy consumption levels, there are other factors that can impact energy consumption at the aggregate level in unelectrified communities. These include rates of consumer connection, presence and scale of productive uses of electricity (PUE) potential in each community, potential and interest in conversion from traditional to e-cooking solutions, and other potential opportunities. The Madagascar IEP has mitigated this uncertainty in multiple coordinated ways.

First, projections of energy consumption at the aggregate level have been evaluated in a comparative fashion with analyses of electrification programmes in other Sub-Saharan African markets and validated against JIRAMA consumption, MTF survey results and ADER statistics for existing mini-grids. In addition, the results of the energy expenditure survey data were also compared to other surveys conducted in East, West and Southern Africa to evaluate reasonableness of the results.

Second, the routing rules that are the basis of the geospatial modelling used to define power system characteristics were defined to integrate uncertainty that is roughly equivalent to increased load by a factor of 15–25 percent. That is to say, the LV and MV distribution networks were designed with conductor sizes that can readily accommodate loads that exceed projected values by 25 percent or more to ensure a high level of reliability; adequate resiliency in the face of significant transients in the distribution networks; and high service quality.

The electrical network design that was derived from the geospatial model, while dependent on the assumed energy consumption, is nonetheless sufficiently robust to accommodate a 15–25 percent increase or decrease in energy consumption without changes required to the distribution infrastructure. This is consistent with best practices in electrification access planning and electric utility long-range planning since electrical infrastructure must be designed for reliability and affordability in a variety of future scenarios, not all of which can be foreseen at the time of the analysis.

No adjustments would be necessary to the grid densification or grid expansion designs in the geospatial models to accommodate a 15 percent increase or decrease in energy consumption. Of these two scenarios, the more severe case is the 15 percent increase, which would increase the load to more than 50 percent of the nominal capacity but would still allow a sufficient margin for there to be no significant change in power quality and no risk of overloading circuits or individual components of the distribution network. Thus, the system has an adequate design margin to accommodate a 15 percent increase in unit consumption. As with other aspects of the geospatial planning, it is assumed that JIRAMA has allocated sufficient resources to long-range generation planning and operational reserves, so their power plants can withstand incremental consumption growth of 15 percent without widespread load shedding or outages.

With respect to mini-grid design, the IEP includes design of both distribution and generation systems. As was mentioned above, the distribution infrastructure in these mini-grids is designed in accordance with national grid standards and with sufficient margin to maintain reliability. Adjustments in energy consumption will, however, impact the design of generation, storage and control components. Fortunately, the mini-grids were dimensioned assuming a 2.4 percent annual population growth and 3 percent annual load growth from 2023 to 2030. Analysis of mini-grid component design was performed using the 2030 consumption forecast. Therefore, the mini-grid results presented in the report exceed the present-day consumption of all mini-grid communities. Moreover, once these mini-grids are implemented, their operators will have several years of operational data to evaluate whether the 2030 load forecast is sufficiently accurate for profitable operations, or whether adjustments should be made in the generation capacity or operational strategy.

For MV mini-grids, increasing energy consumption by 15 percent without redimensioning the power plant resulted in a reduction in renewable energy fraction (RF) from 90.7 percent to 85.1 percent, which led to an 87 percent increase in diesel fuel consumption. However, the net impact on the levelized cost of energy (LCOE) was only USD 0.008/kWh. In the case with 15 percent decreased demand, the RF increased to 94.4 percent and fuel consumption decreased by roughly 50 percent.

For LV mini-grids, increasing energy consumption by 15 percent without redimensioning the power plant will also have operational impacts. Since the LV mini-grids in the baseline case were solar/battery systems without thermal generation, the system will be more sensitive to consumption forecast error. In fact, the 15 percent consumption increase causes 7.8 percent downtime in the solar/battery mini-grid compared to 4.5 percent downtime in the base case. This represents more than 3 percent lost revenue for the mini-grid operator, which will negatively impact profitability. For a 15 percent reduction in LV mini-grid consumption, the unmet load is halved to 2.1 percent, which provides increased reliability to all consumers.

As for standalone solar systems, since all households are receiving tier 2 standalone solar systems (SSS) in the baseline case, it is anticipated that a 15 percent increase in electricity consumption may require households to invest in a tier 3 SSS, which is likely unaffordable for many rural households. Alternatively, a reduction in demand by 15 percent would have no impact on SSS users; since their system would be oversized for their energy needs, they may be able to offer surplus power to their friends or neighbours for lighting or mobile phone charging.

Use Tier 1 as the minimum level of service to support universal access.

As was presented in the financial analysis, the anticipated cost for electricity access in rural Madagascar with tier 2 standalone solar service is USD 350 per standalone solar system or USD 1.56 billion for 4.4 solar standalone systems. If the GoM were to finance USD 180 per system, its cost would be USD 802 million considering a per system subsidy of USD 180. These costs are staggeringly high, so exploring lower-cost alternatives would be useful.

A common approach in universal electrification programmes is to establish a lower minimum level of service. Many countries including Kenya, Malawi, Tanzania, Uganda and others have determined that tier 1 solar solutions are sufficient to satisfy the minimum electrical requirements of most rural households. Lowering the minimum level of service from tier 2 to tier 1 will allow the GoM to reduce solar standalone costs by 49 percent. Moreover, offering tier 1 service as replacement products for aged or dysfunctional solar systems in rural communities would be a far more affordable and popular option for sustaining access.

A comparison of the cost savings that can be realized by changing the minimum level of service from tier 2 to tier 1 is illustrated in Table 21. Note that in the tier 1 scenario, the GoM contribution is reduced by 50 percent and the end-use consumer's payments for SSS replacement are much more reasonable for Malagasy households.

Table 21. Financing requirements to achieve universal access by 2040

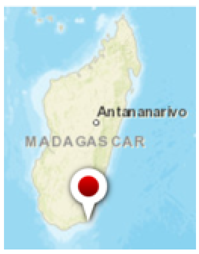
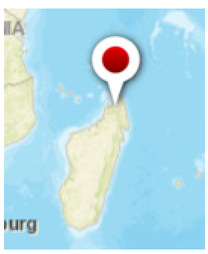
SSS Type	Connections	Total Capital Cost	Cost per Connection (USD)	GoM Financing (USD)	Private Sector (USD)	Consumer Contributions (USD)
Programme costs for Tier 2 SSS electrification						
Standalone solar (SSS)	4,456,299	$1,559,704,692	$ 350	$802,133,842	$ 646,163,372	$ 111,407,478
SSS Replacement	2,628,074	$ 919,825,844	$350	$	$183,965,169	$735,860,675
Total	**7,084,373**	**$2,479,530,536**		**$802,133,842**	**$830,128,541**	**$847,268,153**
Programme costs for Tier 1 SSS electrification						
Standalone solar (SSS)	4,456,299	$802,133,842	$180	$401,066,921	$ 289,659,443	$111,407,478
SSS Replacement	2,628,074	$473,053,291	$180	$	$ 183,965,169	$289,088,122
Total	**7,084,373**	**$1,275,187,133**		**$401,066,921**	**$473,624,612**	**$400,495,600**

Consider all mini-grids as 75 percent renewable that will assume that mini-grids in Madagascar will use a hybrid solar-diesel-storage architecture to generate power.

In the MV mini-grid analysis, the plant sizes are considerably larger (Megawatt scale) than typical mini-grids, Therefore, these mini-grids are considered hybridized in the baseline case analysis. However, the 2,852 LV mini-grids were simulated as fully renewable with 100 percent renewable fraction and only solar and battery equipment – no thermal generation on site for reliability. For these fully renewable mini-grids to be affordable, with CAPEX comparable to an equivalently sized hybrid mini-grid, the solar and battery sizes needed to be reduced to offer less than 100 percent reliability. Thus, the fully renewable mini-grids have a tradeoff in system availability that represents roughly an 8 percent capacity shortage, which results in insufficient operating reserves to operate reliably during some weather and load conditions and 4 percent unmet electricity demand annually, which could lead to customer dissatisfaction and will result in a commensurate loss of revenue for the mini-grid operator.

In analyzing the potential cost savings of hybridizing LV mini-grid systems, HOMER models were generated and compared for three LV mini-grids in the portfolio: the median sized LV mini-grid, the maximum sized LV mini-grid and an intermediate mini-grid representing the upper quartile (75th percentile) of LV mini-grid size in the portfolio. Since the minimum LV mini-grid size according to the analysis criteria is 100 structures and the median is only 126 structures (2023), the median site is believed to represent smaller mini-grids in the portfolio. Results of the HOMER simulation are presented in Table 22.

Table 22. Comparison of LV mini-grid hybridization

	Median MG		Upper Quartile		Largest MG	
Attribute	**100% RF**	**Hybrid**	**100% RF**	**Hybrid**	**100% RF**	**Hybrid**
2030 Peak Demand (kW)	20.2	20.2	24.2	24.2	66.4	66.4
Total HH/Structures 2030	149	149	182	182	516	516
Load Factor	33%	33%	33%	33%	33%	33%
Consumption (kWh/d)	182	182	193	193	530	530
PV Array Capacity (kWp)	57.6	50.3	67.1	61.7	148	140
PV Inverter Capacity (kW)	77.8	67.9	90.6	83.3	199.8	189.0
BESS Capacity (kWh)	145	117	162	135	367	356
Battery Inverter Capacity (kVA)	24.8	20.5	25.2	24.4	70.6	66.8
Diesel Gen Capacity (kVA)	0	25	0	30	0	80
LCOE ($USD)	$ 0.473	$ 0.512	$ 0.448	$ 0.497	$ 0.364	$ 0.419
Renewable Fraction (%)	100.0%	91.0%	100.0%	92.2%	100.0%	94.2%
Initial CAPEX ($USD)	$ 182,614	$ 173,299	$ 206,229	$ 205,304	$ 450,475	$ 484,027
Excess Energy (%)	40.4%	32.5%	42.3%	37.2%	33.0%	29.0%
Unmet Load (%)	4.35%	0.00%	4.45%	0.00%	3.79%	0.0%
Annual Capacity Shortage (%)	8.08%	0.00%	8.03%	0.00%	7.59%	0.0%
Fuel Consumption (L/yr)	0	2564	0	2667	0	4826
Mini-grid Location						

If these results are extrapolated to the entire LV mini-grid portfolio, they can be considerably improved. The mini-grids would all increase their reliability due to the presence of on-site dispatchable generation. Nevertheless, the emissions would be relatively low. The HOMER analysis found that despite the nominal constraint of at least 75 percent renewable fraction, the optimal mini-grid sizing for these grids results in a renewable fraction of 91 percent–94 percent, which indicates that a high level of service can be achieved with a very high renewable fraction in hybrid mini-grids.

Moreover, the hybrid LV mini-grids allow for some cost relief of the CAPEX of solar panels (8 percent) and batteries (17 percent), while achieving even higher grid reliability and a renewable fraction above 90 percent. In either the fully renewable case or the hybrid case, the total number of beneficiaries by 2030 is equivalent: 468,159 connections. The initial CAPEX in the fully renewable case is USD 667 million with over 4 percent downtime whereas the hybrid case has an initial CAPEX of USD 718 million (not including diesel fuel costs) with 0 percent downtime.

In addition, SEforALL has requested the analysis of two additional sensitivities to the electrification analysis, which include the potential for hydropower plants to provide generation systems for isolated mini-grids, and the impact of agricultural PUE on the electrification plan. The approaches for both sensitivities and their analysis will be included in the final electrification report and final consolidated report.

RECOMMENDATIONS

Madagascar is the world's second largest island country with a population just under 30 million people that has one of the highest poverty rates in Southern Africa. The current reported electrification rate is approximately 35 percent (2023, Tracking SDG7 Report) while access to clean cooking devices is far lower at just 12 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) through this IEP, offers 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.

With this in mind, a set of key strategic recommendations is put forward as a complement to the electrification planning presented in this report. These recommendations are organized by electrification modality.

Densification: JIRAMA reported 621,776 customers in 2022, of which 95 percent are residential. Data provided by JIRAMA indicate that approximately 100,501 consumers were connected between 2018 and 2022, at a rate of about 20,000 per year. Densification potential is highest in the urban and peri-urban areas of Madagascar. Analamanga, the region that includes Antananarivo, accounts for 38 percent of the densification potential of the entire country. As is show in Table 23, the estimated densification CAPEX requirements are estimated at just under USD 560 million, which accounts for nine percent of the total CAPEX budget need to meet the 2030 universal access goal. Notably, this nine percent of total CAPEX can add an estimated 1.6 million connections, or 14 percent of the total future required connections. The financial efficiency of densification among electrification modalities demonstrates the priority for JIRAMA to actively develop and pursue a densification programme, as is considered under the Least-Cost Electricity Access Development (LEAD) project. However, expansion of connections must come with equal expansion of generation, transmission and distribution infrastructure improvements to ensure power quality and availability of supply – both in JIRAMA's interconnected networks as well as isolated systems. In the interest of densifying its isolated grids, JIRAMA will need to conduct a holistic condition assessment of the isolated grids both in terms of generation and distribution assets to determine if these systems will need to be rehabilitated to ensure power quality and supply adequacy prior to commencing a densification programme. As importantly, JIRAMA must undertake a concerted effort to reduce non-technical losses, conduct and apply a robust cost of service review, among other measures, to ensure it is financially stable enough to expand its consumer base.

Grid Expansion: Grid expansion has the potential to serve up to 1 million new connections as the grid is currently constituted. Like densification, expansion of connections must come with equal expansion of generation, transmission and distribution infrastructure improvements to ensure power quality and availability of supply. At present, the JIRAMA national grid is relatively limited without much transmission capability. Therefore, grid expansion in the Integrated Energy Plan (IEP) is limited to 15 km from existing medium voltage (MV) infrastructure. To expand its existing networks into more remote areas, JIRAMA may need to consider mechanisms for voltage support on its distribution feeders, including but not limited to distributed generation and reactive power equipment. These investments could allow for longer, more cost-effective

MV grid expansion, but additional funding will be necessary to bring these future assets online. That said, grid expansion provides a least-cost path to the electrification of communities and facilities that are currently located near existing and functioning infrastructure. However, given JIRAMA's present financial constraints, the pace and aggressiveness of the grid expansion programme needs to be aligned with its financial realities.

Moreover, the IEP models allow for grid expansion from JIRAMA's 96 isolated grids in order to promote leastcost electricity access in the surrounding communities not presently served by JIRAMA. Nevertheless, to consider these sites for grid expansion, JIRAMA will need to conduct a holistic condition assessment of the isolated grids both in terms of generation and distribution assets to determine if these systems will need to be rehabilitated to ensure power quality and supply adequacy prior to commencing an expansion programme. JIRAMA may also choose to consider hybridizing the power supply in its isolated systems to reduce the fuel cost, OPEX and greenhouse gas emissions (GHG) associated with its operational fleet of small diesel generators serving isolated grids – an undertaking it is starting now.

JIRAMA could take initial steps to prepare for a grid expansion programme, which would include but are not limited to: 1) digitizing transmission, distribution and customer meters, leading towards refined and actionable distribution and transmission plans; 2) conducting a cost of service study and refining the tariff methodology with the goal of improving financial sustainability while recognizing consumer affordability limits, which is understood to be under development at the end of 2023 as part of the project titled "Elaboration of regulatory texts framing the regulation of electricity sales tariffs in Madagascar"; 3) tackling non-technical losses through revenue protection programmes aimed at measuring and actively reducing non-technical losses transformer by transformerThis list of actions is certainly not exhaustive but would empower JIRAMA to make data-driven decisions that would enable it to invest in grid expansion in the year to come.

Mini-grids: The results of the IEP have shown that there is significant potential for both large-scale MV mini-grids at the Megawatt scale and community sized low voltage (LV) mini-grids for hundreds of customers. A considerable share of the total CAPEX budget for universal access could be dedicated to both MV and LV mini-grid developments as is shown in Table 23, at 45 percent of the total CAPEX requirements corresponding to over USD 3.1 billion. Prior to making such large investments, several strategic steps should be taken to ensure investments in mini-grids have the lasting impacts they are designed for, which include evaluating and standardizing system-design standards and materials specifications; developing a comprehensive service territory delineation approach building off of the AP process currently underway within ADER; continuing to rationalize mini-grid tariffs; and developing a tariff methodology that is transparent and equitable across developers and consumers alike.

In terms of the mini-grid enabling environment, Madagascar ranks in the lower half of countries with a Regulatory Indicators for Sustainable Energy (RISE) score of 52 on a 100-point scale. RISE is a framework used to analyze and compare regulatory frameworks based on the promotion of mini-grid development[41]. Clear tariff regulation for mini-grids helps establish clearer viability criteria for mini-grid developers while offering more uniform consumer

[41] ESMAP, Mini Grids for Half a Billion People, 2022.

protection for mini-grid customers. As such, regulatory oversight, consumer protection and homogenization of tariff structures could benefit the off-grid sector as it develops. In addition, the private sector's role will need to be incentivized taking into consideration the private sector's need to earn a reasonable return on investment in the face of significant affordability issues for low-income community members. Madagascar is one of the first countries in Sub-Saharan Africa where results-based financing (RBF) incentives are available for mini-grid developers. These types of programmes will be critical to accelerating the Malagasy mini-grid sector and will need to be perpetuated and expanded to meet the deployment goals specified in the IEP.

Standalone solar: Standalone solar solutions will likely play a pivotal role in meeting universal electrification goals. Their ability to be easily replicated and distributed to suit the electricity needs of a variety of loads, combined with the ability to provide power in any setting – urban, rural, remote – unlock a powerful tool in solving the access challenge. However, these advantages must also be countered with policies and programmes that ensure that high-quality products are bought and sold, and that replacement of antiquated systems is both accounted for in programme financing as well as in terms of how systems are sustainably retired or repurposed, among other considerations. The private sector will play an important role in providing the standalone solar solutions to the market, but policies and programmes are needed to ensure that sufficient capital is available to meet the scale of the need, that quality of products is ensured, and to safeguard against new standalone solar connections not solely being stacked in otherwise electrified areas – meaning, a programme must be designed to ensure that standalone solar solutions are able to meet the rural and remote consumers that would normally be left out if no incentives are put in place.

Table 23. Requirements to achieve universal access by 2030

Electrification Modality	Total Future Connections	% of Total Future Connections	Total CAPEX	% of Total CAPEX
Densification	1,598,572	14%	$599,464,500	9%
Grid Expansion	1,034,027	9%	$762,662,830	11%
MV Mini-Grids	1,435,019	12%	$2,522,679,025	36%
LV Mini-Grids	466,122	4%	$667,221,243	9%
Standalone Solar (SSS)	4,453,214	38%	$1,558,624,896	22%
SSS Replacement	2,628,074	23%	$919,825,844	13%
Total	**11,615,027**		**$7,030,478,338**	

Other cross-cutting considerations with regards to the strategic implementation of the IEP include:

- A clear and effective electrification strategy and programme management framework is needed to ensure that multiple and complementary activities can be effectively implemented in a coordinated manner to result in a steady progression of electrification progress. Through the Planning Unit, this mechanism has been established within the Ministry of Energy and Hydrocarbons (MEH), but the mechanisms, procedures and practices needed to effectively plan, finance and scale up electrification expansion have not yet been put into practice. That is, the key modifications and coordination will be needed to support the scale of activities that are now needed.

- A holistic and integrated GIS is needed to guide the electrification access and expansion planning across the MEH, JIRAMA, and ADER. While the IEP will deliver the database and web visualization platform needed for initial geospatial electrification planning, the next step is for a proper GIS to be developed to house and maintain the spatial datasets related to each electrification modalities expansion and to track investments and gaps in access nationwide.
- It is recommended that the GIS be managed by ADER, with data-sharing workflows between JIRAMA and the MEH. The main challenge for the GIS will be to define the processes needed to routinely collect data to ensure the database is up to date. This will require that JIRAMA fully digitize its distribution system, that private sector mini-grids digitize their systems, and that a process is put in place to capture all new electrification infrastructure geospatially.
- Consumption levels in rural areas of Madagascar as evaluated through the energy expenditure surveys may not support private-sector investment in rural and remote areas of Madagascar, particularly if solutions include solar and/or hydropower resources to supply electricity. Electrification expansion in income-challenged areas will require higher subsidies and incentive programmes to achieve the growth levels defined by the IEP.
- Affordability is a very significant risk that will need to be addressed through cost-sharing through ambitious improvements in efficiency, economies of scale and ultimately cost-sharing between JIRAMA, the GoM, private developers, local government and consumers. The magnitude of the overall investment and the ability of private-sector investors to raise the capital they will need raises additional concerns about achieving the very aggressive electrification expansion goals that are defined in this document.
- Improved integration and use of spatial and non-spatial planning tools within MEH, ADER and JIRAMA are needed to better coordinate, target and realize national electrification goals. Use of geospatial platforms and data is quite limited in each agency, which hinders planning on a national scale and for the substantial access gaps that must be addressed.

Through the electrification analysis and recommendations provided above, this electrification report of the Madagascar IEP supports improved energy and electrification policy development as well as providing 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.

ANNEX

A1 - Routing Rules for Madagascar

Madagascar Integrated Energy Plan

Universal Electrification Routing Rules

Prepared by: NRECA International, June 2023

Preface

The following discussion explains NRECA International's proposed methodology for the geospatial electrification modelling for the Madagascar Integrated Energy Plan (IEP). The geospatial processing consists of multiple sequential steps, as documented in the Inception Report. First, the structures are clustered into transformer-level low voltage (LV) networks, grouped to minimize technical losses, and assigned energy consumption and peak demand. Then medium voltage (MV) networks are routed along existing roadways to interconnect the clusters in a least-cost optimization algorithm. Finally, the clusters are differentiated by least-cost electrification modality: grid densification, grid expansion, mini-grids and standalone solar systems.

The detailed assumptions and methodology for each step in the analysis is provided.

Parameters for Clustering

The clustering algorithm will link buildings (rooftops) into clusters as the basis for electrification analysis. The primary parameters for establishing the electrification clusters are defined below.

Clustering Radius

Clustering is developed based on the number of households within a 600 m radius around a transformer location. To determine the number of households in a cluster, the number of rooftops visible in the cluster will be multiplied by the ratio of households to rooftops as follows:

Households to rooftops ratio: 1.04 (Household/Digitized Structure)

This ratio is used to determine how many consumers are represented by each digitized structure in the geodatabase. Typically, the ratio is less than 1 in rural areas, where individual households may comprise multiple structures, whereas the ratio is greater than 1 in urban areas due to multi-family housing. For the Madagascar IEP, NRECA evaluated the 2018 population and household values per district and region from the RGPH and calculated 2023 values using the population growth rate of 2.4 percent. The 2023 estimates of households per district and region were compared to the count of structures digitized (2023) per region, which resulted in a national average of 1.04 household per structure. A ratio of 1.04 households per structure will be used as a national average for clustering, however NRECA can differentiate this value by region in the final electrification analysis by district and region.

Demand Formula

The demand of the cluster for purposes of design should be calculated using the REA demand equation:

$$Demand = C*(1-0.4*C+0.4*(C^2 + 40)^{0.5}) *0.0059256*B^{0.885}$$

Where:

C= The number of consumers in the cluster (= rooftops *1.04)

B = The weighted average consumption 26 kWh/month/consumer for the year ten of the project for structures beyond 15 kilometers from known JIRAMA distribution grids/systems

B = The weighted average consumption 61 kWh/month/consumer for the year ten of the project for structures within 15 kilometers from known JIRAMA distribution grids/systems, and. (see Annex A1 and A2 for weighted average consumption assumptions)

Cluster size: urban and peri-urban

For structures within 15 km of JIRAMA grids: – The minimum allowable number of rooftops in the cluster is 10. This will load a 15 kVA transformer to 35 percent of its rating at year ten. Clusters with fewer than 10 rooftops should be redesigned or designated as standalone solar systems (SSS).

Cluster size: rural

Grid expansion: For structures beyond 15 km of JIRAMA grids: The minimum allowable number of rooftops in the cluster is 40. This will load a 15 kVA transformer to 35 percent of its rating at year 10. Clusters with fewer than 40 rooftops should be redesigned or assigned to SSS. Mini-grids with total clusters within a 1000 m radius with fewer than 100 rooftops should be redesigned or assigned to SSS.

Transformer assignment and sizing

Transformers serving the clusters should be sized so that they are 50 percent loaded at year 10, as calculated above (see demand table, Annex A1 and A2). This allows for additional flexibility in the clean cooking plan for higher e-cooking assumptions without redesigning the distribution system. The smallest transformer size allowed is a 15 kVA single-phase transformer. Transformers of 15 kVA and 25 kVA will be single phase, since single-phase transformers are preferred for economic reasons. Transformers larger than 25 kVA will be three phase with a minimum size of 50 kVA. Transformers should not be located at street or road intersections but should be in mid-block so that the transformer has two outlets, each covering a roughly equal load.

Transformer sizes allowed are as follows:

a. 15 kVA - Single phase 20kV/230-460V

b. 25 kVA - Single phase 20kV/230-460V

c. 50 kVA - Three-phase 20kV/400 single Pole-mounted

d. 100 kVA - Three-phase 20kV/400V

e. 200 kVA - Three phase 20kV/400V

Productive use of energy (PUE) and industrial loads

Industrial customers should be located manually as fixed points from the surveys, which were not completed during this pre-feasibility phase. If the consumer is identified as a mill, the point load demand is assumed to be 25 kW, and a 50 kVA three-phase dedicated transformer will be installed at the location. For load estimation purposes, only industrial consumers identified from future field surveys should be counted. These assumptions will be revisited based on results of primary data collection and energy expenditure analysis.

Low Voltage (LV) Level

LV voltage is 400/230V for three-phase LV and 230V single phase for single-phase LV.

Demand levels and transformer sizing

Demand tables for clustering and transformer allocation are shown in Annex A1 and A2, costing table for all equipment is attached as Annex A3 and load assumptions are attached as Annex A4 and A5.

Parameters for Defining LV/MV Routing

Once the clusters have been fully defined, an LV routing algorithm will follow existing road rights of way to bring the LV network within an acceptable distance of each structure that is suitable for a customer drop and metered connection. A separate algorithm will define the medium voltage (MV) routing to interconnect the clusters. The MV routing will also follow existing roadways and other public rights of way, avoiding water, naturally protected areas and other predefined obstacles.

Both the MV and LV routing algorithms will assign incremental costs to each additional connection to the grid expansion. Thus, the algorithms are capable of assigning cumulative costs to each proposed expansion of the grid and determining when further expansion becomes cost-prohibitive relative to off-grid electrification modalities.

LV routing

LV is to be routed as follows:

a. Three-phase LV is to be used for LV in clusters that require three-phase transformers. Conductor for three-phase LV lines is **twisted insulated cable with carrier neutral** 54.6 mm^2 for all three-phase transformers. Three-phase transformers must have at least two

LV circuits and for a 50kVA or 100 kVA transformer, two ABC 54.6mm^2 circuits are adequate. For clusters that require a transformer larger than 100kVA with a 600m radius, a 200kVA transformer can be installed, but more than two LV circuits leaving the transformer will be required. Two LV lines can be placed on a single pole so that a single transformer can serve up to four LV circuits even if it is in the centre of the block. Load limits for three-phase ABC 54.6 mm^2 quadruplex LV conductor and a 600m radius of service is 45kW per LV circuit. Three-phase transformers with 600m radii of service, therefore, require the following number of LV circuits:

i. 50 kVA: 1 circuit though 2 are preferred.

ii. 100 kVA: 2 circuits

iii. 200 kVA: 4 circuits

b. Single-phase LV designed for 230V single-phase service can be used for clusters that require single-phase transformers of 25kVA or less and shall be **self-supporting twisted insulated cable** ABC 35mm^2. Load limit for ABC 35mm^2 with a radius of service of 600m is 12 kW per LV circuit. There should be two LV circuits of ABC 35mm^2 leaving any single-phase transformer.

Medium voltage (MV) routing

The MV voltage for rural service is 35 kV, 20kV, and 15kV in a three-wire ungrounded system (system neutral grounded at substation). It is proposed that single-phase 15kVA, 25kVA and three-phase 50kVA transformers are installed in a single pole to reduce cost while transformers of 100kVA or more are to be installed on H frame structures (two poles). For purposes of cost, we will not assume any underbuild of LV conductors on MV lines. That is, MV lines and LV lines will be separate systems with separate lines of poles, coming together only at the transformers. MV and LV lines should be plotted on separate layers in the GIS and their costs calculated separately.

a. Routing of 20kV MV shall be as follows:

i. Main lines shall follow main roads and ideally would interconnect substations, although this may not be possible as the substations may be very distant. Communities along the main road will be served from the main line.

ii. Communities not on the main line should be served by laterals tapped off the main line, not by detouring the main line through the community. Laterals serving cumulative loads of 600 kW or less at the 10-year load level can be two-phase (phase to phase) lines if there are no three-phase transformers in the communities being served. Two-phase lines are preferred as laterals for economic reasons. No single-phase laterals from 15kV line. Laterals may have a maximum length of 10 km and their length would be included in the line length considered in the figure below.

iii. Laterals serving three-phase transformers or with a total load more than 600 kW at the 10-year level will be three phase. Three-phase laterals should also be limited to 15 km but may have loads of up to 1000 kW for 20kV and 1500 kWfor 35kV.

b. Conductor sizes for MV should be chosen as follows:

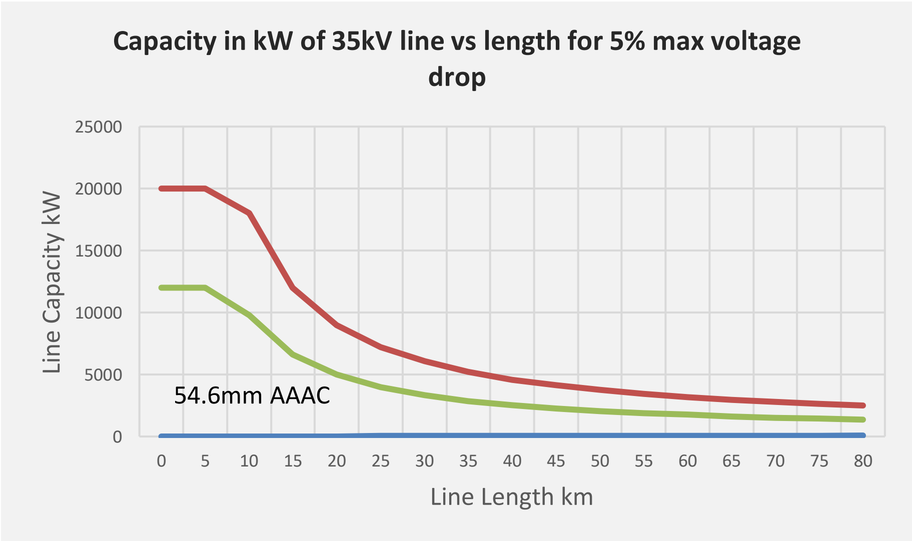
   i. Main feeder conductors shall be 117mm^2 AAAC.

   ii. Three-phase lateral conductors shall be 54.6mm^2 AAAC

   iii. Two- phase (two energized phase wires) lateral conductors shall be 34.4mm^2 AAAC (only from 35kV and 20kV)

Conductor capacity and maximum allowable loading chart

Conductor	Amps Capacity (MAX)	Suggested 50% loading (amps)
117mm^2 AAAC.	369	
54.6mm^2 AAAC	224	112
34.4mm^2 AAAC	167	



Parameters for determining electrification modality in off-grid clusters

At the completion of the previous step, all structures in Madagascar will be digitized and assigned to a geospatially optimized cluster of suitable radius and population density, with transformer and conductor sizing commensurate to the electricity demand in the cluster. Optimal LV internal routing has been completed within each cluster and optimized MV routing among the various clusters is constrained by (a) maximum MV expansion radius (15 km for 20 kV) and (b) incremental cost constraints.

Distinguishing between grid expansion and off-grid clusters

When performing the MV routing, it will be optimal to add additional clusters to the national grid if the incremental cost of doing so is sufficiently low in terms of capital expenditure (CAPEX) per connection, allowing economies of scale for grid connection. If the CAPEX cost of adding the cluster to the national grid is lower than the hypothetical CAPEX per connection of new mini-grid construction, then the least-cost approach from an IEP standpoint will be to add the cluster to the JIRAMA grid.

If the CAPEX per connection is below USD 1,250 per connection, the cluster will be considered for grid expansion. If the CAPEX per connection exceeds USD 1,250 per connection, the cluster will be considered for off-grid electrification.

New Sources:

Given that the interconnected JIRAMA grid is quite limited in geographical scope, and additionally less than 100 isolated towns are electrified by standalone JIRAMA metro grids, NRECA used a methodology to establish new metro-grid generation/substations sites to expand and scale electrification efforts throughout the country. These steps included:

1. The results of the clustering analysis were used to identify areas of the country with a significant number of clusters but no existing interconnected grid or isolated grid.
2. In these areas (# number were identified), the larger population centre(s) were visually identified using satellite imagery, then a suitable site was found at the periphery of this larger population centre and along a major road that could serve as suitable generation/substation site.
3. A new generation source point was created at these locations, from which a 20 kV backbone feeder was designed such that it could be used to route new MV feeders to interconnect available clusters of load.

Refining MV routing:

Given the varied terrain features in Madagascar, as well as key protected areas, large old growth forests, rivers, etc., NRECA deployed several geospatial routing rules to refine the MV line alignments designed within the GIS. In particular, the MV routing was restricted to only be allowed to follow existing roads to cross or enter protected areas or larger forests, in addition, large rivers were only crossed where an existing road and bridge were assumed to exist based on the available data. Furthermore, contour and topographical data layers were used to limit the MV routing over the substantial mountain range that divides the eastern coast from the highlands in central Madagascar.

Distinguishing between mini-grid and SSS clusters

For the off-grid clusters, additional parameters will need to be evaluated to determine the optimal off-grid electrification modality. In the Madagascar IEP, the off-grid clusters will be classified as metro-grids, mini-grids, and SSS. The primary distinguishing factor will be the total electricity demand in each cluster, which can be approximated by the number of connections in the cluster.

Clusters of fewer than 100 connections within a 1,000 m radius will be considered for SSS electrification. Clusters of more than 100 connections within a 1,000 m radius will be considered for LV mini-grids.

Within clusters that are assigned to mini-grids, the LV routing algorithm will evaluate the incremental costs of connection. If any of the structures within the proposed MV/LV mini-grid cluster require more than USD 2,000 per connection, then these structures will be excluded from the mini-grid and assigned to SSS.

Distinguishing between LV mini-grids and MV metro-grids

If multiple clusters assigned to LV mini-grids are located within 15 km, then interconnection of the LV mini-grids will be evaluated using the MV routing algorithm. Although adding MV will increase the CAPEX per connection of the distribution system, there are potential cost savings in larger economies of scale in the generation plant to serve the consolidated MV system rather than individual small-scale power plants to serve each LV mini-grid.

If the LV clusters are within 15 km and the levelized cost of energy (LCOE) is decreased by adding MV routing and transformers due to generation economies of scale, then the system will be defined as an MV metro-grid with a single, centralized generation plant. The MV metro-grids will have solar-battery-diesel hybrid generation plants with a renewable energy fraction of at least 75 percent.

If the LV clusters are separated by more than 15 km or the LCOE is increased due to the MV routing connections, then each LV cluster will be defined as an LV mini-grid with its own generation plant. The LV mini-grids will have fully renewable power plants with solar and batteries, but no diesel.

Methodology for LCOE calculation

The LCOE will be determined from a representative sample of the entire LV mini-grid cluster dataset. The mini-grids will be ranked in terms of number of connections and the median-sized mini-grid will be simulated in HOMER to determine the optimal dimensioning of solar and storage, the ratio of solar array kWp, solar inverter kW, battery kWh, and battery inverter kW as a proportion of each mini-grid's peak demand kW. These ratios will be held constant for evaluating the generation CAPEX for all LV mini-grids.

The CAPEX cost basis for LV mini-grid analysis will be based on a literature review of mini-grid costs tailored to the Madagascar market. For LV mini-grids with fewer than 300 connections, the CAPEX assumptions will reflect smaller capacity equipment and higher unit costs. For LV mini-grids exceeding 300 connections, the CAPEX assumptions will reflect larger capacity equipment purchased in bulk for larger mini-grid portfolios.

The CAPEX cost basis for MV metro-grids will use volume pricing to reflect utility-scale procurement capabilities for Megawatt-scale equipment. The MV routing and transformer assumptions will be comparable to the costs used in the grid expansion analysis.

NRECA will evaluate LCOE for mini-grids and metro-grids in comparison to grid expansion via the JIRAMA grid using the cost of generated or purchased power in USD/kWh.

JIRAMA isolated grids

JIRAMA isolated grids will be buffered to 600 meters to set an electrified area within which only densification will be analyzed, grid expansion from JIRAMA isolated grids will then be routed to the 15 km limit for 20 kV in the base case. At present, NRECA has been unable to confirm whether these systems are in good operating condition or whether they are operating with excess capacity for expansion. It is likely that grid expansion from the JIRAMA isolated grids will require significant grid rehabilitation of the MV and LV networks to enable higher connection rates (densification) as well as customer growth (expansion), which cannot be accurately determined at present.

Off-grid sensitivity analysis

In addition to the base case analysis described previously, NRECA will perform the following sensitivity analyses:

1. Simulate the LV mini-grids as solar-battery-diesel hybrids rather than 100% renewable fraction. For this sensitivity, the renewable fraction will exceed 75 percent.
2. Consider mini-hydroelectric potential in LV mini-grids and evaluate LCOE. The 2017 World Bank Small Hydro Atlas will be used as the database of potential small hydro sites. In addition, low season precipitation (May to October) appears to be significantly reduced everywhere but the eastern coast of Madagascar. In this region we could propose including some of the known potential hydro sites from the World Bank Atlas to be used as generation sources and thus routed to serve nearby structures/communities.
3. Consider hybridization of existing JIRAMA isolated systems to include solar and batteries that minimize diesel consumption with a renewable energy fraction of at least 75 percent.

Annex A1: Demand Table for Use in Clustering in Areas within 15 kms of a JIRAMA Grid

Consumers	Peak Demand kW at 61 kWh/Consumer/mo.	Transformer kVA
5	2.5	N/A
10	3.9	N/A
15	5.1	15
20	6.3	15
25	7.4	15
30	8.5	25
35	9.7	25
40	10.8	25
45	11.9	25
50	13.1	50
60	15.3	50
70	17.6	50
80	19.8	50
90	22.1	50
100	24.3	50
125	30.0	100
150	35.6	100
175	41.2	100
200	46.9	100
225	52.5	200
250	58.1	200
275	63.8	200
300	69.4	200
325	75.0	200
350	80.6	200
375	86.9	200
400	91.9	200
425	97.5	200
450	103.2	200

Annex A2: Demand Table for Use in Clustering in Areas beyond 15 kms of a JIRAMA Grid

Consumers	Peak Demand kW at 26 kWh/Consumer/mo.	Transformer kVA
5	1.2	N/A
10	1.8	N/A
15	2.4	N/A
20	2.9	N/A
25	3.5	N/A
30	4.0	N/A
35	4.5	N/A
40	5.1	15
45	5.6	15
50	6.1	15
60	7.2	25
70	8.3	25
80	9.3	25
90	10.4	25
100	11.4	25
125	14.1	50
150	16.7	50
175	19.4	50
200	22.0	50
225	24.7	50
250	27.3	100
275	30.0	100
300	32.6	100
325	35.3	100
350	37.9	100
375	40.6	100
400	43.2	100
425	97.5	200
450	103.2	200

Annex A3: Cost Summary Assumption (using SSA regional costs)

MV Lines and Transformers				
Item	**Type**	**Size**	**Rate ($)**	**Unit**
35 kV Line	AAAC	117mm2	$33,810	$ per km
	AAAC	54.6mm2	$29,150	$ per km
35 kV Line Two-phase (phase to phase)	AAAC	34.4mm2	$24,849	$ per km
Transformers	35/0.4 three phase			
		350 kVA	$14,835	$ / Unit
		100 kVA	$11,380	$ / Unit
		50 kVA	$6,670	$ / Unit
	30/230 single phase	25kVA	$4,070	$/Unit
		15kVA	$3,520	$/Unit
20 kV Line	AAAC	117mm2	$29,400	$ per km
	AAAC	54.6mm2	$26,500	$ per km
20 kV Line Two-phase (phase to phase)	AAAC	34.4mm2	$22,590	$ per km
Transformers	20/ 0.4 three phase			
		200 kVA	$12,900	$ / Unit
		100 kVA	$10,800	$ / Unit
		50 kVA	$5,800	$ / Unit
	30/230 single phase	25kVA	$3,700	$/Unit
		15kVA	$3,200	$/Unit
15 kV Line	AAAC	117mm2	$28,518	$ per km
	AAAC	54.6mm2	$25,705	$ per km
Transformers	15/ 0.4 three phase			
		150 kVA	$12,513	$ / Unit
		100 kVA	$10,476	$ / Unit
		50 kVA	$5,626	$ / Unit
LV Line and Service Drops				
0.4 kV three phase Twisted insulated cable with carrier neutral	ABC	95 mm2	$21,800	$ per km
0.4 kV three phase Twisted insulated cable with carrier neutral	ABC	54.6mm2	$16,300	$ per km
0.23 kV Self-supporting twisted insulated cable	ABC	35mm2	$12,900	$ per km
Service Drop Cost, single-phase consumers			$160	per connection
Service Drop Cost, three phase consumers			$255	per connection
JIRAMA low-cost connection			$80	per connection

Annex A4: Load Assumptions (structures within 15 kms of JIRAMA grid)

Input customers and consumption assumptions	Unit	Input Value
Household annual growth (World Bank – based on pop growth rate)	%	2.4%
Consumers Mix (Source: JIRAMA 2022 consumer data)		
Residential	%	95.00%
Commercial	%	5.00%
Medium Industrial	%	0.004%
Total	**%**	**100.00%**

Input initial penetration rates and annual growth

Consumption and annual growth	Unit	Year 1	Growth yr 2-5	Growth yr 6-10
Residential (Source: ADER & AFD)	kWh/Cust-month	40	2.0%	2.0%
Commercial & Institutional (rural JIRAMA)	kWh/Cust-month	240	3.5%	2.0%
Medium Industrial (rural JIRAMA)	kWh/Cust-month	11900	5.0%	2.0%
		Year 1	Year 5	Year 10
Weighted Average for clustering	kWh/Cust-month	**50**	**55**	**61**
Penetration rates	Unit	Year 1	Years 2 - 5	Years 6-10
Residential	%	25%	50%	70%
Commercial & Institutional	%	50%	65%	82%
Medium Industrial	%	90%	90%	100%
	Unit	Year 1	Year 5	Year 10
Distribution system losses	%	15.00%	14.00%	12.00%

Annex A5: Load Assumptions (structures beyond 15 kms of JIRAMA grid)

Input customers and consumption assumptions

	Unit	Input Value
Household annual growth (World Bank – based on pop growth rate)	%	2.4%
Consumers Mix (Source: ADER, JIRAMA, consultant estimation)		
Residential	%	99.00%
Commercial	%	1.00%
Medium Industrial	%	0.000%
Total	**%**	**100.00%**

Input initial penetration rates and annual growth

Consumption and annual growth	Unit	Year 1	Growth yr 2-5	Growth yr 6-10
Residential (Source: ADER & AFD)	kWh/Cust-month	19	2.0%	2.0%
Commercial & Institutional (Source: rural JIRAMA)	kWh/Cust-month	240	3.5%	2.0%
Medium Industrial (Source: rural JIRAMA)	kWh/Cust-month	11900	5.0%	2.0%
		Year 1	Year 5	Year 10
Weighted Average for clustering	kWh/Cust-month	**21**	**23**	**26**
Penetration rates	**Unit**	**Year 1**	**Years 2 - 5**	**Years 6-10**
Residential	%	25%	50%	70%
Commercial & Institutional	%	50%	65%	82%
Medium Industrial	%	90%	90%	100%
	Unit	**Year 1**	**Year 5**	**Year 10**
Distribution system technical losses (LV mini-grids)	%	5%	5%	5%
Distribution system technical losses (MV mini-grids)	%	6%	6%	6%
Distribution system non-technical losses	%	8%	6%	5%

B1 - Grid Expansion Project List

Separate Excel attachment. They are not viewable as a table in Word.

B2 - Mini-grid Project List

Separate Excel attachment. They are not viewable as a table in Word.

C1 - Hydropower potential for unelectrified Madagascar

This chapter of the consolidated report of the Madagascar IEP assesses the hydropower potential for unelectrified Madagascar.

Background

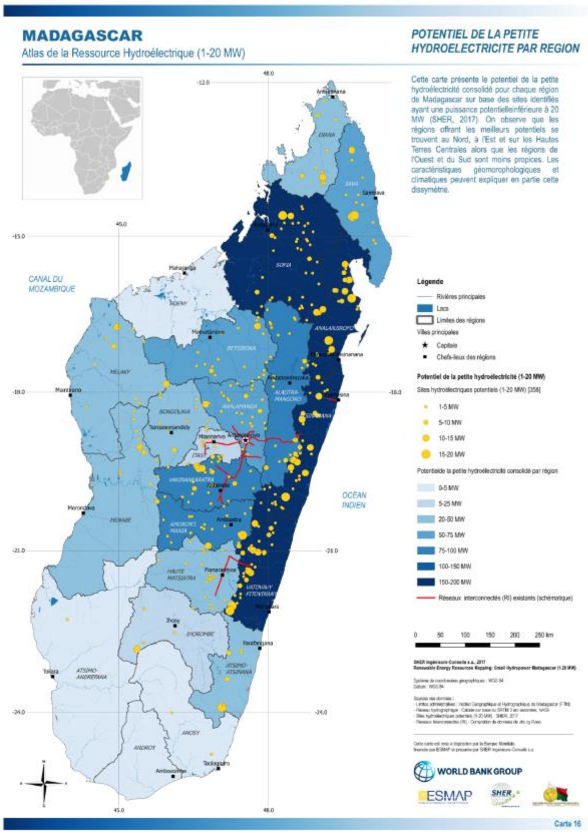
The electrification analysis undertaken in support of the Madagascar Integrated Energy Plan (IEP) evaluates demand for electrification services in conjunction with an analysis of electrification solutions. For communities and housing clusters that are within 15 kilometers of JIRAMA electricity generation-distribution service, the IEP electrification analysis focused primarily on satisfying the electrification needs of unelectrified communities with JIRAMA service. Expansion of existing private mini-grid service was also evaluated for unelectrified communities and housing clusters.

The majority of unelectrified communities in Madagascar are beyond the immediate reach of JIRAMA and existing private mini-grid service providers. For all of these communities, an evaluation of off-grid service options was conducted, including the option of forming mini-grids powered by hydroelectric resources. Small hydroelectric service has the potential of offering relatively low-cost electricity service with relatively low maintenance requirements, and with higher reliability than conventional thermal generators, and in some cases, higher reliability than solar-diesel hybrid generation stations. However, small hydroelectric generation is subject to variations in stream flow throughout a 12-month hydrology cycle. For this reason, when small hydroelectric stations are considered as the sole source of power for isolated mini-grids, it is very important to evaluate the potential with multiple years of stream flow data that are collected and recorded continually throughout the year – that is, to understand streamflow throughout an annual hydrologic cycle.

Hydroelectric Data for Madagascar

Hydropower resources in Madagascar are significant, diverse and have the potential to contribute significant generation capacity and energy to JIRAMA and private, independent electricity distribution service providers. Hydroelectric resources have been assessed and quantified in several independent efforts, notably aggregated and reported in the World Bank-sponsored Hydropower Atlas[42] . The Hydropower Atlas begins with a presentation of the geography of Madagascar, then has a description of the energy sector in Madagascar, followed by a detailed assessment of small hydropower resources (less than 20 MW) and a presentation of geographic locations, a quantification of hydroelectric potential and general descriptions of all sites included in the small hydroelectric database. A map that presents high-level data from the Hydropower Atlas is presented in Figure 39. While the Hydropower Atlas is an extremely useful resource, the data and analysis presented in it support preliminary analyses; more detailed streamflow data are required to validate site potential for investment analysis purposes. Twelve-month streamflow data are required for investment analysis of standalone power supply solutions for mini-grids with which power supply availability and reliability could be modelled for an entire generation-distribution year. Moreover. site potential is evaluated using the month of lowest streamflow.

Figure 39. Hydropower Atlas – small-scale hydropower potential by region



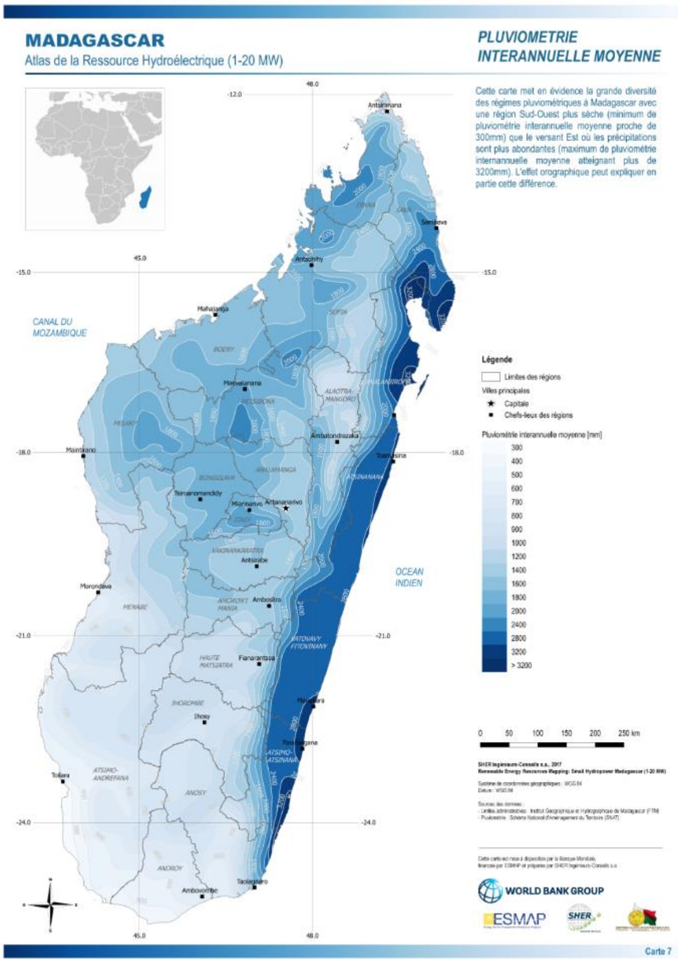
Taking this into account, this section presents the methodology that was used in the IEP analysis to evaluate hydroelectric mini-grid potential in Madagascar.

[42] *Small hydro resource mapping in Madagascar (Vol. 3) : Hydropower Atlas : final report (English).* Energy Sector Management Assistance Program Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/712621504691635966/Hydropower-atlas-final-report

Hydropower Atlas site screening methodology for mini-grid power supply

This section describes the methodology to prioritize small hydropower sites that could be developed to power mini-grids identified in the Madagascar IEP electrification analysis. The first step to evaluate site viability is to determine low season streamflow as a function of rainfall levels in the watershed associated with each site. A geographic analysis of rainfall patterns reveals that rainfall levels vary significantly by region in Madagascar. The highest rainfall levels are recorded along the eastern coast that faces the Indian Ocean with significantly lower rainfall in all other regions. Figure 40 illustrates rainfall levels by geographic region taken from the Hydropower Atlas. Areas with lower rainfall levels are also subject to multi-month dry seasons that extend from April to October. By contrast, rainfall on the eastern coast has much lower seasonal variation.

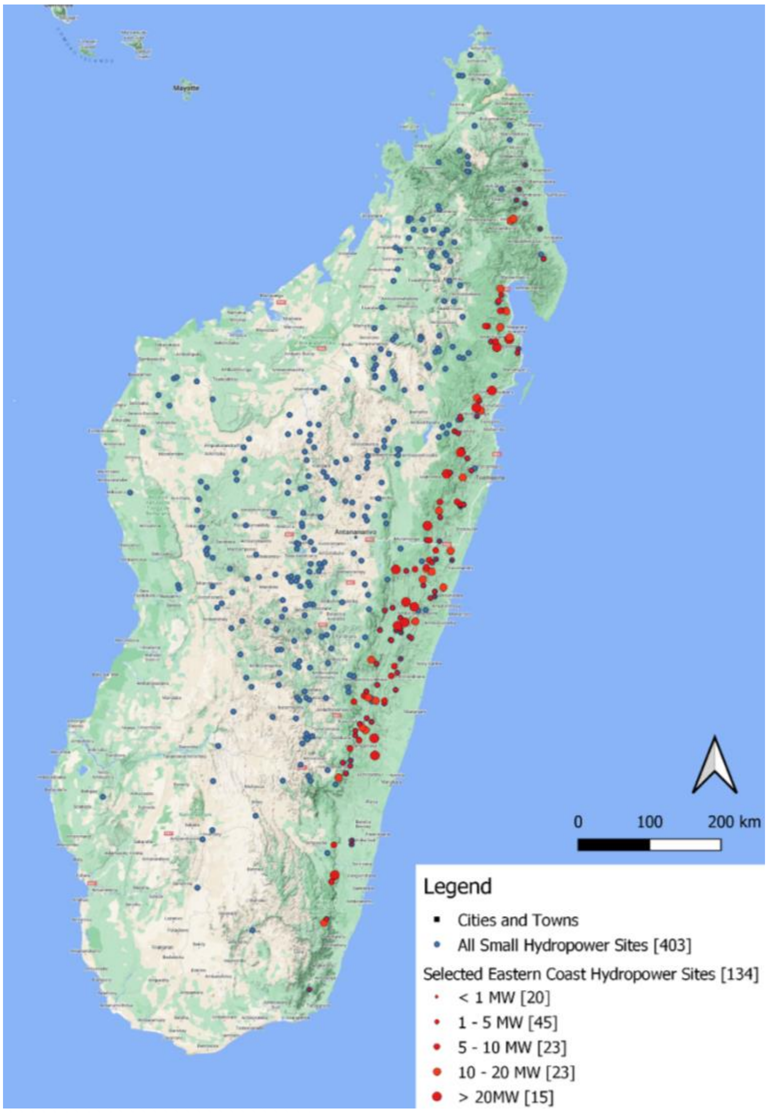
Figure 40. Hydropower Atlas – annual average rainfall



Taking into account higher rainfall with lower seasonal variability, mini-grids that could be powered by hydroelectric resources were identified and evaluated on or near the eastern seaboard. From the list of 403 hydropower sites shown in the Atlas, 138 sites in the eastern seaboard were prioritized. Given that this is a high precipitation zone, rainfall levels in the 138 sites range from 1,169 mm to 2,799 mm.

The Hydropower Atlas not only identifies hydroelectric sites in suitable watersheds, it also uses digital terrain models (DTM) algorithms to evaluate gross head for all sites. While the analysis for all but 17 sites was performed using satellite imagery and rainfall data, as opposed to on-site surveys, the results presented in the Hydropower Atlas nonetheless provide sufficient resolution to match hydropower potential with load requirements using the IEP geospatial electrification model. As such, for practical purposes, sites with gross head over 15 meters were selected. Figure 41 illustrates the hydropower sites selected after applying this last screening parameter.

Figure 41. Selected eastern coast hydropower sites in excess of 15 meters of gross head



Once the hydroelectric characteristics of the sites in the Hydropower Atlas were migrated to the IEP geospatial electrification model, the most important step in evaluating hydropower mini-grids was to evaluate how close the hydroelectric sites are to load centres that were classified as mini-grids. Housing clusters aggregated with sufficient demand to be developed as MV mini-grids were geo-processed with the hydroelectric sites within 15 kilometers of one another. After matching potential hydropower sites with MV mini-grid locations, the hydropower site cost projections were performed using a parametric analysis and unit costs for medium and higher-head hydro sites.

Potential hydropower contributions to mini-grid power supply

After evaluating the Hydropower Atlas hydroelectric sites with aggregated demand via the geospatial electrification analysis, 41 small hydropower sites identified that lay within 15 km of 26 mini-grids. These sites were selected for further analysis. Table 24 presents the 26 mini-grids organized by region, with the hydropower sites that are within 15 kilometers of these mini-grids. Note that multiple hydropower sites were identified within 15 kilometers of 16 of the 26 selected MV mini-grids.

Table 24 also shows mini-grid demand in MW assuming full penetration of all potential household and commercial consumers, as well as the estimated hydropower capacity in MW as reflected in the Hydropower Atlas. Note that only seven mini-grid sites show demand levels that exceed hydropower capacity; these are shown in red font in Table 24. Also note that projected hydroelectric capacity exceeds mini-grid demand by a factor of 40, meaning that hydroelectric sites would unlikely be developed to power mini-grids unless they could be developed at a much lower capacity than shown in the Hydropower Atlas.

The hydroelectric sites are shown in Table 24, while all mini-grid projects are shown in Figure 43.[43]

Table 24. Comparison of MV mini-grids with small hydropower sites that are within 15 km

Region	MV Mini-grid Name	Hydropower Site Name	Mini-grid Demand (MW)	Estimated Hydropower Capacity (MW)
Alaotra Mangoro	**Ss_58_Moramanga**	SF420	0.47	3
Analanjirofo	**Fenerive_Est2**	ANTOHAKA	0.66	0.5
	Mananara_Avaratra_Ss	AMBOHITRARI	0.60	14
		SF530	0.37	11
		SF532	0.60	14
	Mananara_Avaratra_Ss2	Vohibato	0.71	16
		Vohipary	0.71	39
	Ss_44_Maroantsetra_1	AMBODIRIANA	0.76	14
		ANDRATAMBE	0.76	4
	Ss_45_Maroantsetra_1	ANDRATAMBE	0.79	4
		MAHERIVARAT	0.79	136
		SF536	0.79	8
	Ss_46_Maroantsetra_1	ANDRATAMBE	0.26	4
		MAHERIVARAT	0.26	136
		SF536	0.26	8
		SF540	0.26	4
		SF541	0.26	10
	Ss_47_Mananara_Avaratra	ANJAHAMBE	0.69	2
		SF530	0.69	11
	Ss_48_Mananara_Avaratra	AMBOHITRARI	0.45	7

[43] Note that these mini-grid names can be referenced in the geospatial datasets and mini-grid project lists provided with this report.

		SAHANDRAZAH	0.45	1
		SF532	0.45	7
	Ss_724_Fenerive_Est	ANTOHAKA	0.67	0.45
		SF019	0.67	12
		SF020	0.67	36
	Ss_725_Fenerive_Est	SF019	1.44	12
		SF020	1.44	36
		SF108	1.44	3
	Ss_726_Mananara_Avaratra	IlengyB	0.30	9
		SAHANDRAZAH	0.30	1
		SF530	0.30	11
Atsimo Atsinanana	**Befotaka_Ss**	MASIMBOLA	0.19	18
		SF213	0.19	4
	Ss_72_Farafangana	ANTANATOMEN	0.48	0.42
		BEMANGEVO	0.48	0.43
	Vangaindrano_Ss1	KAPOKAPOKA	0.37	6
Atsinanana	**Ss_715_Mahanoro**	SF022	0.30	19
	Vatomandry_Ss	SF025	0.15	11
		SF431	0.15	1
		SF432	0.15	1
Fitovinany	**Manakara_Atsimo_Ss**	Ambatosada	0.64	85
Sava	**Ss_18_Sambava**	SF489	0.53	1
	Ss_19_Sambava	SF489	1.00	0.60
	Ss_20_Sambava	SF489	0.58	1
		SF491	0.58	1
	Ss_23_Sambava	ANDAMPIBE	0.91	0.50
	Ss_25_Antalaha	ANDRANOLAVA	1.03	0.33
Vatovavy	**Ifanadiana_Ss1**	ANDRIAMPIDI	0.12	7
		Behingitika	0.20	4
	Ifanadiana_Ss2	Andriamanjavona	0.46	26
		Anosy	0.11	12
		ANTALAY	0.23	6
		SF195	0.58	15
		Tambohorano	0.58	15
	Ss_70_Ifanadiana	SF038A	0.30	25
Grand Total			**29.56**	**831**

Figure 43. Filtered small hydropower sites and selected mini-grids within a 15 km radius

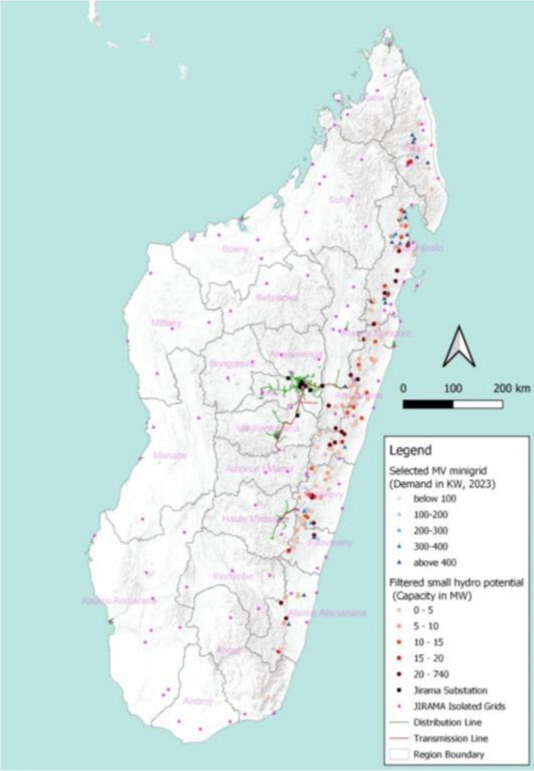
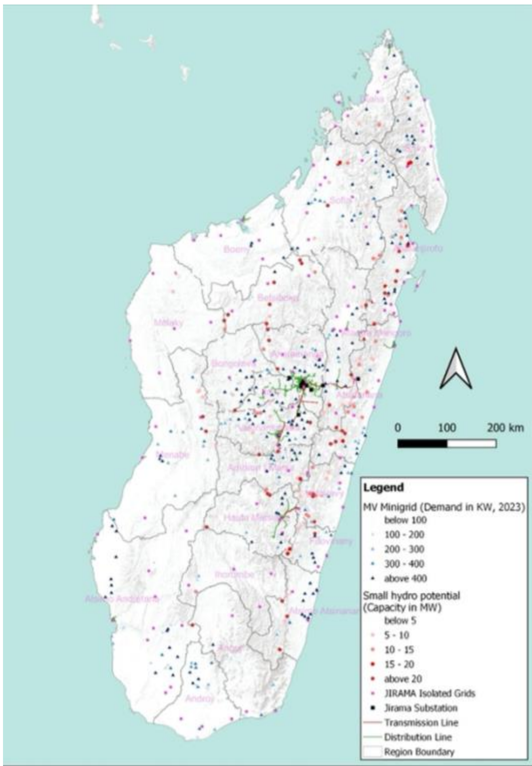


Figure 42. Full site lists - small hydropower sites and MV mini-grids



It is important to recognize that the Hydropower Atlas does not provide development cost estimates of the hydroelectric sites, but rather presents estimated hydroelectric capacity of these sites. Estimation of development costs requires more detailed site-specific analysis. Geotechnical challenges, topographic anomalies and challenges to match optimal site capacity with electricity demand contribute to design, procurement and construction costs. For the purposes of this analysis, an average CAPEX development cost equivalent to USD 4,000 per installed kW has been used in consultation with energy specialists in Madagascar. The development cost estimates can be divided roughly into approximately 60 percent of overall capital requirements for civil works and 40 percent for electro-mechanical equipment – meaning penstocks, powerhouses, turbines, generators, controls and substation requirements. Table 25 provides the estimated capital development costs for the hydropower sites for two use cases, one in which the system is designed to exploit the full capacity of the hydropower resources, and the other in which the design is set to the mini-grid full-penetration demand. Note that downsizing a hydroelectric facility can often result in increasing the unit cost of capacity, so the figures presented in Table 25 are intended to be notional only; site-specific analysis is needed to provide improved cost estimates for hydro mini-grid opportunities.

While hydropower will play an important role in electrification expansion in Madagascar and continued economic development, further site-specific feasibility is required to ensure that hydropower resources are properly designed, costed and exploited. The tables and spatial data generated by this analysis should provide a lens under which potential hydropower feasibility study may be further prioritized, particularly for the development of new off-grid access in Madagascar.

Table 25. Hydropower CAPEX estimates.

Region	MV Mini-grid Name	Hydropower Site Name	Hydropower Full Resource Capacity CAPEX (USD)	MG Peak Demand Hydropower CAPEX
Alaotra Mangoro	**ss_58_moramanga**	SF420	$10,340,000	$1,868,400
Analanjirofo	**fenerive_est2**	ANTOHAKA	$1,800,000	$2,648,400
	mananara_avaratra_ss	AMBOHITRARI	$57,040,000	$2,418,800
		SF530	$43,160,000	$1,462,000
		SF532	$54,560,000	$2,418,800
	mananara_avaratra_ss 2	Vohibato	$64,320,000	$2,824,000
		Vohipary	$155,576,000	$2,824,000
	ss_44_maroantsetra_1	AMBODIRIANA	$54,600,000	$3,032,800
		ANDRATAMBE	$17,880,000	$3,032,800
	ss_45_maroantsetra_1	ANDRATAMBE	$17,880,000	$3,167,200
		MAHERIVARAT	$544,600,000	$3,167,200
		SF536	$32,720,000	$3,167,200
	ss_46_maroantsetra_1	ANDRATAMBE	$17,880,000	$1,040,800
		MAHERIVARAT	$544,600,000	$1,040,800
		SF536	$32,720,000	$1,040,800
		SF540	$16,480,000	$1,040,800
		SF541	$38,280,000	$1,040,800
	ss_47_mananara_avaratra	ANJAHAMBE	$7,640,000	$2,765,600
		SF530	$43,160,000	$2,765,600
	ss_48_mananara_avaratra	AMBOHITRARI	$28,520,000	$1,818,400
		SAHANDRAZAH	$5,080,000	$1,818,400
		SF532	$27,280,000	$1,818,400
	ss_724_fenerive_est	ANTOHAKA	$1,800,000	$2,665,200
		SF019	$46,260,000	$2,665,200
		SF020	$142,400,000	$2,665,200
	ss_725_fenerive_est	SF019	$46,260,000	$5,745,200
		SF020	$142,400,000	$5,745,200
		SF108	$11,720,000	$5,745,200
	ss_726_mananara_avaratra	IlengyB	$36,012,000	$1,215,600
		SAHANDRAZAH	$5,080,000	$1,215,600
		SF530	$43,160,000	$1,215,600
Atsimo Atsinanana	**befotaka_ss**	MASIMBOLA	$72,960,000	$769,600
		SF213	$15,040,000	$769,600

	ss_72_farafangana	ANTANATOMEN	$1,680,000	$1,906,400
		BEMANGEVO	$1,720,000	$1,906,400
	vangaindrano_ss1	KAPOKAPOKA	$25,600,000	$1,480,800
Atsinanana	**ss_715_mahanoro**	SF022	$77,224,000	$1,211,200
	vatomandry_ss	SF025	$43,520,000	$607,600
		SF431	$3,320,000	$607,600
		SF432	$4,360,000	$607,600
Fitovinany	**manakara_atsimo_ss**	Ambatosada	$339,272,000	$2,553,600
Sava	**ss_18_sambava**	SF489	$2,400,000	$2,105,600
	ss_19_sambava	SF489	$2,400,000	$3,983,200
	ss_20_sambava	SF489	$2,400,000	$2,320,400
		SF491	$3,800,000	$2,320,400
	ss_23_sambava	ANDAMPIBE	$2,000,000	$3,625,600
	ss_25_antalaha	ANDRANOLAVA	$1,320,000	$4,109,200
Vatovavy	**ifanadiana_ss1**	ANDRIAMPIDI	$27,200,000	$463,200
		Behingitika	$15,520,000	$782,800
	ifanadiana_ss2	Andriamanjavona	$102,240,000	$1,848,800
		Anosy	$48,800,000	$426,400
		ANTALAY	$22,480,000	$903,600
		SF195	$58,800,000	$2,326,000
		Tambohorano	$59,760,000	$2,326,000
	ss_70_ifanadiana	SF038A	$98,640,000	$1,193,200
Grand Total			**$3,323,664,000**	**$118,254,800**

C2 – Demand aggregation in the IEP

This chapter of the consolidated report of the Madagascar IEP addresses the various use-specific electricity loads that are considered in the IEP: e-cooking, agricultural cooling, healthcare/healthcare cooling, productive uses, and how they can be characterized for future analysis and utilization as part of the integrated IEP results.

Demand analysis approaches

Geospatial data on existing productive use of electricity (PUE) infrastructure is limited in Madagascar. It is important to note that the electricity consumption estimates used in electrification modelling include a combination of residential and commercial requirements, as well as public facility loads. That is, electricity consumption and demand are estimated in two ways in the IEP:

- **Aggregated approach used in geospatial electrification planning** - Through an aggregated approach in the geospatial electrification planning process, based on observed total consumption/month for various consumer types (residential, commercial, industrial) on the basis of reported data from ADER, JIRAMA, and PTF projects (e.g. AFD, World Bank). This approach provides a robust, applicable estimate of consumption for consumers that accounts for both household and non-household demand and is appropriate for a national least-cost planning exercise. This is the approach that is used in the geospatial electrification planning.
- **Disaggregated approach for use-specific load potentials** - Through a disaggregated approach that seeks not to reconstitute a full demand forecast or load profile but rather to characterize and spatialize specific types of demand linked to energy use cases such as e-cooking, cooling and refrigeration, social infrastructure or productive uses of energy that may have important implications on the socio-economic impact of electrification (as for social infrastructure and some types of PUE) and/or on levels of consumption and load profiles in the areas where they occur. Given the difficulties of predicting where some of these loads may occur, data limitations, and other factors, this approach may not be fully adapted to a national infrastructure planning exercise. However, it provides important information that can nuance or supplement the more aggregated approach taken for the electrification plan. In addition, while these specific loads are not spatially represented in the electrification plan, transformers serving the clusters were sized so that the average load did not exceed 50% of transformer capacity at year 10. This provides ample transformer capacity at the planning stage to accommodate more site specific loads during project feasibility study.

The sections below provide a summary of the parameters and guiding results of each demand approach, which are also visualized on the Madagascar IEP visualization platform.

Aggregated demand estimation used in geospatial electrification planning

As presented in the IEP electrification report, the Rural Utilities Services, a United States government agency, developed a regression formula[44] that is comprised of two factors – number of consumers and average monthly energy consumption in kWh. This formula was used to calculate peak demand by dividing the digitized structures in Madagascar into two categories – A) structures *beyond* 15 kilometers from known JIRAMA distribution grids/systems, and B) structures *within* 15 kilometers from known JIRAMA distribution grids/systems. With this distinction, two estimates were used for the average monthly energy consumption in kWh based on a 10 year projection of the likely consumer mix (residential, commercial, industrial) and average monthly electricity consumption per consumer type, while the count of structures was used as the number of consumers. The weighted average consumption for year ten of the project for structures beyond 15 kilometers from known JIRAMA distribution grids/systems is **26 kWh/month/consumer**, while the weighted average consumption for year ten of the project for structures within 15 kilometers from known JIRAMA distribution grids/systems is **61 kWh/month/consumer**. Again, all transformers were sized so that the average load did not exceed 50% of transformer capacity at year 10. The sources and parameters used to develop these consumption estimates are found in the electrification report.

Disaggregated use-specific load potentials

Disaggregated use-specific electric loads can be derived from several sources. Presented in this section are the potential contributions to electricity consumption and demand from:

- Health facilities electrification
- E-cooking
- Agriculture cold chain equipment electrification
- Electrification of grain mills for rice and maize processing
- PUE applications

Note that the specific loads are not geospatially defined in the electrification analysis rather they are represented in the assumptions for weighted average consumption per customer per month. The subsections below provide insights into the potential use-specific loads that could be analyzed on a project by project basis as electrification projects are implemented in Madagascar.

Health Facilities

The electrification of health facilities is a major policy goal of the Government by 2030. The table below is an extract from the IEP medical cold chain report showing the likely on-grid (either through grid expansion or MV mini-grid) demand requirements for each type and count of heath facility (for health facilities that are to be electrified). The sizing of demand is derived from the facility equipment estimates summarized in the report, which were then used to estimate the

[44] See https://www.rd.usda.gov/resources/regulations/bulletins, REA Bulletin 45-2, Demand Tables

average added kW demand by electrification modality. In total, average demand for all grid connected health facilities is estimated to be on the order of 4.2 MW, whereas MV mini-grid health facilities could add an additional 435 kW of demand in total.

Table 26. Health Facilities electrification modality and demand estimation (Source: Madagascar IEP, 2023)

Type of Facilities	Hybrid System Sizing		Future electrification modality		Demand Estimation	
	Energy Consumption kWh/day	PV Array Size (kWp)	Facilities electrified by Grid Expansion	Facilities electrified by MV Mini-grid	Added Grid kW	Added MV Mini-grid kW
CHD	29	8	0	0	0	0
CHR	133	38	1	0	133	0
CHRD	133	38	16	5	2133	190
CHRR	133	38	2	0	267	0
CHU	146	42	0	0	0	0
CRNM	133	38	1	0	133	0
CSB1	1	0	75	132	103	63
CSB2	1	0	152	204	209	98
DISP/MAT	1	0	0	0	0	0
DPEV	146	42	0	0	0	0
DRSP	133	38	4	0	533	0
Hosp	146	42	0	0	0	0
SDSP	29	8	25	10	735	84
Grand Total			**276**	**351**	**4246**	**435**

E-cooking

Electricity access makes e-cooking solutions potentially viable in certain geographical regions of Madagascar, particularly in the major urban centers electrified by JIRAMA's interconnected electricity network, subject to cultural acceptance, affordability analysis, and other adoption constraints. As part of the IEP, e-cooking is considered viable for grid-connected and grid-edge systems, and not viable for isolated systems or locations with no access (see table below). Isolated mini-grids and standalone systems are generally considered to be designed to have insufficient power capacity for cooking, and have high end-user tariff that are cost prohibitive for cooking outside a very small amount of customers relative to other fuel and stove types as identified in the clean cooking survey, and the corresponding use of e-cooking in rural areas is reflected in this study. As such, the table below provides a summary of which electrification modalities were analyzed for e-cooking potential in the IEP.

Table 27. E-cooking potential by electrification modality

E-cooking Possible (grid connection)	E-cooking Not Possible (isolated connection)
JIRAMA existing	Isolated MV mini-grid
JIRAMA densification	LV mini-grid
JIRAMA expansion (Interconnected)	SSS
JIRAMA expansion (Isolated)	No access
Grid Edge MV Mini-grid	

The table below provides the household energy needs to cook using both an electric hot plate and electric induction plate, which were used in the IEP clean cooking study to evaluate e-cooking potential for the two scenarios. The clean cooking report uses Mj per year to calculate energy needs, which are converted into kWh per year, month, and day. Note that cooking with hot plates and induction plates would increase the household monthly consumption by 60 to 120 percent respectively. However note that not all households will utilize e-cooking, and that while these specific cooking loads are not spatially represented in the electrification plan, transformers serving the clusters were sized so that the average load did not exceed 50% of transformer capacity at year 10. This provides ample transformer capacity at the planning stage to accommodate more site specific loads during project feasibility study.

Table 28. Household e-cooking needs

Households - Final Energy Needs to Cook				
Stove type	Mj/year	kWh/year	kWh/month	kWh/day
Electric - hot plate	4,003	1,112	91	3
Electric - induction plate	2,778	772	63	2

As such, as part of the clean cooking study, e-cooking potential was analyzed for 2023 and 2030. The results of this analysis are shown in the figures below, wherein e-cooking is shown as a percentage of the population per commune that would be envisioned to be able to utilize e-cooking as a stove solution. This provided flexibility in the clean cooking plan for higher e-cooking demand assumptions within the thermal capacity of transformers and distribution lines without explicitly redesigning the distribution system for varying levels of e-cooking adoption scenarios. In addition, the table below provides a summary of the aggregate e-cooking energy use for 2023 to 2030 for households and institutions, for both scenarios, for Madagascar.

Table 29. Aggregate e-cooking energy use for 2023 to 2030 for households and institutions, for both scenarios.

	Energy Use for Cooking for Households (GWh)		Energy Use for Cooking for Institutions (GWh)	
	Compact Baseline Scenario	IEP Universal Scenario	Compact Baseline Scenario	IEP Universal Scenario
2023	73.9	19.3	73.9	19.3
2024	303.1	31.4	363.7	45.3
2025	544.0	47.5	664.0	71.6
2026	796.9	64.6	975.0	98.6
2027	1,062.0	82.1	1,296.6	126.2
2028	1,339.5	100.5	1,629.2	154.4
2029	1,629.4	117.8	1,972.8	183.0
2030	1,931.8	136.6	2,327.3	212.5

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Footnote

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Abbreviations

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