Assessment of the Techno-Economic Potential of Rooftop PV

at Sites of Interest in South Africa



RES4AFRICA FOUNDATION

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ABBREVIATIONS

AI	Artificial Intelligence
BESS	Battery Energy Storage System
COCT	City of Cape Town
CF	Capacity Factor
DOD	Depth of Discharge
DSM	Digital Surface Model
EA	Enumeration Areas
GHI	Global Horizonal Irradiance
HD	High Demand
LCOE	Levelized Cost Of Energy
LD	Low Demand
NPC	Net Present Cost
NPV	Net Present Value
NTCSA	National Transmission Company South Africa
OB	Open Buildings
OSM	OpenStreetMaps
POC	Proof-of-Concept
PV	Photovoltaics
PVGIS	Photovoltaic Geographical Information System
RES	Renewable Energy Sources
SANLC	South African National Land Cover
SOC	State Of Charge
SSEG	Small-Scale Embedded Generation

1. INTRODUCTION

In recent years, South Africa has seen a surge in interest in rooftop PV installations, which more than doubled over the past two years, growing from around 2 GW in 2022 to approximately 6 GW in 2024, according to the latest Generation Adequacy Report by the National Transmission Company of South Africa (NTCSA), formerly the Eskom Transmission Department, which will hereinafter be referred to as NTCSA. This substantial increase in variable renewable generation requires careful integration into the power system, impacting both distribution and transmission grids and necessitating appropriate measures to ensure system security and reliability.

Within the framework of the previous study commissioned by RES4Africa to CESI, Integration of Non-Programmable Renewable Energy in the National Electric System of South Africa - Phase 2, the maximum integration capacity of V-RES and BESS in the South African system was assessed. The study highlighted that while the system faces constraints due to limited infrastructure to transfer power from the South-Western to Northeastern regions, the integration of BESS, strategic curtailment practices, and the complementary nature of wind and PV resources offer valuable solutions to maximize renewable energy usage. In this context, the installation of rooftop PV at the distribution level provides added benefits at local level but may limit the potential for additional utility-scale PV, as its power output during central daily hours cannot be easily curtailed or dispatched by NTCSA.

In light of these findings, NTCSA and RES4Africa recognized the importance of studying potential future rooftop PV penetration to inform transmission planning processes.

The specific objective of this work is therefore to develop a robust methodology for assessing and modelling the technical and Economically Viable Potential of rooftop PV and BESS installations in South Africa. This methodology is tested as a proof of concept in a case study focused on Cape Town Municipality, offering insights into possible outcomes and scenarios that NTCSA can later replicate across other regions with varying assumptions and boundaries.

In terms of overall objective, the extended application of the methodology developed and tested in this study aims at significantly enhancing NTCSA's planning and grid operating efforts, as it enables more accurate forecasting of the future potential of rooftop PV and BESS in South Africa. In turn, improved planning has positive implications for the V-RES IPP sector, fostering a more reliable integration pathway and supporting the growth of independent renewable energy producers.

The work is structured into the following Sections:

- Section 2. **METHODOLOGY**: it describes the definition of the methodology for the assessment of the techno-economic potential of rooftop PV in South Africa, focusing on assumptions and calculations. Two phases, – namely the technical and the economic potential analyses, including an overview on state-of-the-art models and tools, – are separately presented and described.
- Section 3. **DATA COLLECTION**: the section describes the data collected from COCT and NTCSA for the Proof of Concept (POC) applied to the Cape Town Municipality.
- Section 4. **PROOF OF CONCEPT (POC)**: it presents the numerical results of the application of the methodology to the Cape Town Municipality.

In the ANNEX A-PROCEDURES, the details for replicating the procedure by NTCSA are reported.

2. METHODOLOGY

The goal of this Section is to outline the steps of a methodology able to assess the potential of rooftop PV in sites of interest in South Africa and scalable to the whole country.

The potential for rooftop PV installations can be subdivided into:

- *Technical Potential*: it is the achievable maximum capacity (MW) and generation (GWh) of rooftop PV given system performance, rooftop area availability and additional constraints. Technical potential provides an upper-boundary estimate of the rooftop PV development potential in a particular area.
- *Economically Viable Potential*: it is a subset of the Technical Potential and accounts for the benefits (i.e., economic and reliability) related to investment in rooftop PV and BESS technology. It considers costs for the technologies, as well as electricity tariff costs, eventual incentives, the expected return on investment, and security of supply indexes. The Economically Viable Potential would identify the maximum capacity (MW) and generation (GWh) that would be installed to achieve the expected benefits.

The Technical and Economically Viable Potential will be evaluated as two subsequent steps: the Technical Potential phase returns a set of output results that are useful to have a complete overview of the context per se and returns input data that are used in the next Economically Viable Potential phase as well.

The methodology is be based, among others, on:

- Geospatial data analysis to assess the buildings footprints, the solar resource availability and to characterize the buildings.
- Techno-economic evaluations to identify the optimal size of PV and BESS systems for different users' categories.

A first schematic vision of the methodology is reported in the following ***Figure 1***.

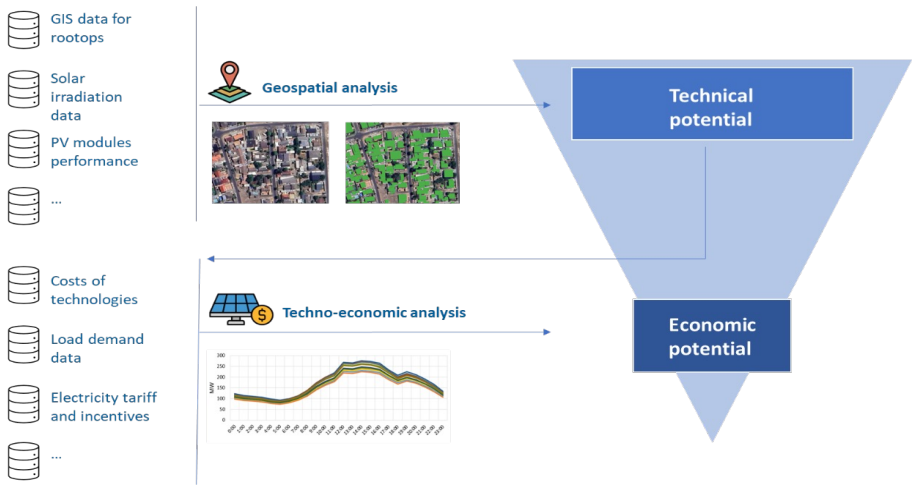


Figure 1: Overall process flowchart

2.1. TECHNICAL POTENTIAL

The PV Technical Potential refers to the maximum installable solar photovoltaic systems in terms of kW, given the available space on the existing rooftops, and a set of constraints, but without considering economic or market factors (they are investigated in the Economically Viable Potential). It is a measure of the total amount of electricity that could be potentially generated by PV systems ***if*** all usable surfaces were covered with solar panels. It depends on the available solar resource, usable area for PV deployment, efficiency of the PV modules and geographical position.

The methodology for computing the Technical Potential is composed by 4 Steps, outlined in the flow chart of ***Figure 2***. It is based on geospatial analysis that could be performed with the most common tools for GIS data processing, i.e. QGIS[1] and ArcGIS[2].

In the ANNEX A-PROCEDURES, the detailed procedures are described.

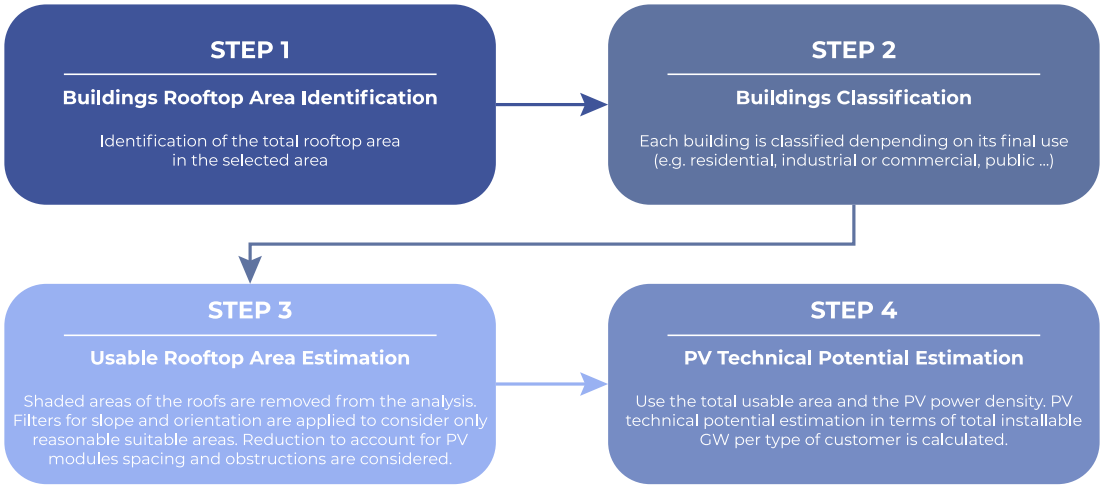


Figure 2: PV Technical Potential flow chart

This section outlines the methodology for assessing the Technical Potential across the entire South African territory. The methodology is then demonstrated in the «Proof of Concept» section, focusing on the Cape Town municipality.

2.1.1. Step 1: Buildings Rooftop Area Identification

This step involves providing a guide on how to effectively identify all existing buildings throughout the South African territory, based on the available information and data.

[1] *https://www.qgis.org/*
[2] *https://www.arcgis.com/index.html*

2.1.1.1. Input

The first step of the procedure requires the building footprint data of the area of interest. The primary data sources can be different open-source geospatial databases as well as specific data provided by stakeholders active in the territory:

- Open Street Map.
- Open Buildings.
- Rooftop data from municipalities.

2.1.1.1.1. Open Street Map (OSM)

It envisages the extraction of the polygons tagged as "buildings" in the OSM database in the South African territory. Quoting the official Wiki page of OSM, "OpenStreetMap is a free, editable map of the whole world that is being built by volunteers largely from scratch and released with an open-content license".[3] OSM allows the use of its Overpass API for search queries that return geometries from OSM's map features (i.e., points, lines, and polygons) for their processing in GIS tools and software. OSM is updated and maintained by a community of volunteers via open collaboration, which means its updates do not follow a predefined schedule.

In order to establish the accuracy of this database for South Africa, an example of the results from this first sub-step is shown in the image in ***Figure 3***, which reports a comparison between OSM data and the © 2023 Google Earth satellite image of a residential area in the selected area.

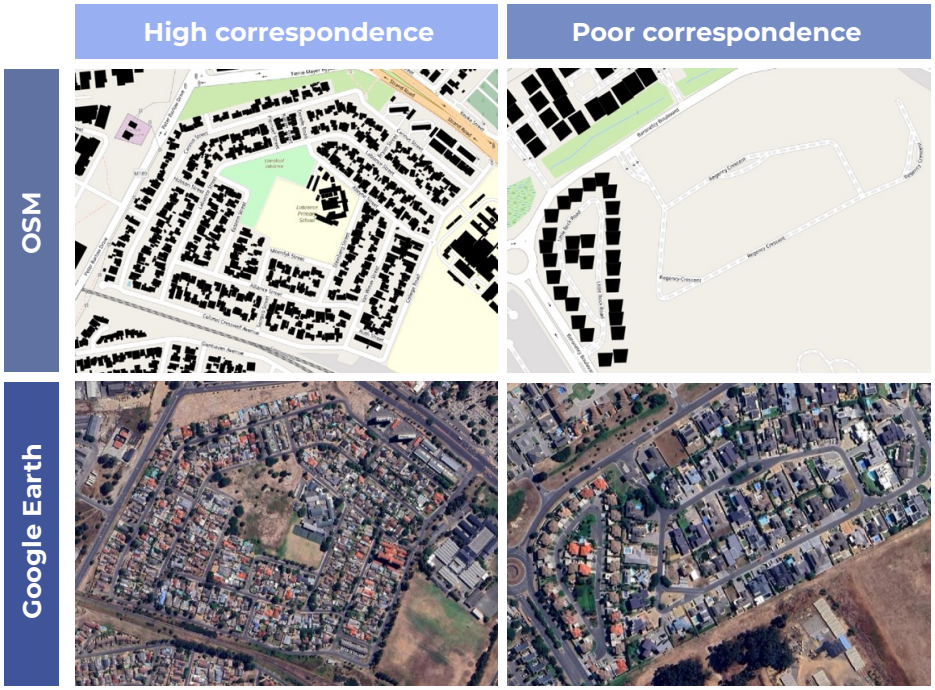


Figure 3: Comparison between OSM's building features and the © 2023 Google Earth satellite image

[3] *https://wiki.openstreetmap.org/wiki/About_OpenStreetMap*

In South Africa, some zones are mapped with high accuracy and building are properly identified, others appear poorly mapped, with only few detected buildings. Due to these disparities, relying on OpenStreetMap for comprehensive analysis across the entire South African context is not recommended, as it may lead to incomplete or inaccurate results. To achieve a more consistent and reliable analysis, an alternative approach is suggested.

2.1.1.1.2. Open Buildings (OB)

Open Buildings[4] is a dataset of building footprints to support social good applications. The dataset contains 1.8 billion building detections, across an inference area of 58M km2 within Africa, South Asia, South-East Asia, Latin America and the Caribbean. The current dataset is in its 3rd version (v3), updated in 2023.

Building polygons and points are stored in spatially shaded CSVs with one CSV per S2 cell level 4. Each row in the CSV represents one building polygon or point and has the following columns:

- Latitude: latitude of the building polygon centroid.
- Longitude: longitude of the building polygon centroid.
- Area_in_meters: area in square meters of the polygons.
- Confidence: confidence score [0.65;1.0] assigned by the model.
- Geometry: the building polygon in the WKT format (polygon or multipolygon) (this feature is present only in polygon data).
- Full_plus_code: the full Plus Code at the building polygon centroid.

There is no information about the type of building, its street address, or any details other than its geometry.

The dataset is created with artificial intelligence techniques starting from satellite images retrieved from Google Earth. The procedure envisages the extraction of the polygons tagged as "buildings" in the OB database in the interested municipality.

An example of the results from this first sub-step is shown in the image in ***Figure 4***, which reports a comparison between OB data a satellite image of a residential area in Cape Town city centre, showing a very high level of correspondence between the OB's building features and the actual buildings.



Figure 4: Comparison between Open Building's polygon layer with a satellite image of the same area

[4] *https://sites.research.google/gr/open-buildings/*

To explain better what the confidence score is, it is possible to analyse the graph reported in ***Figure 5***.

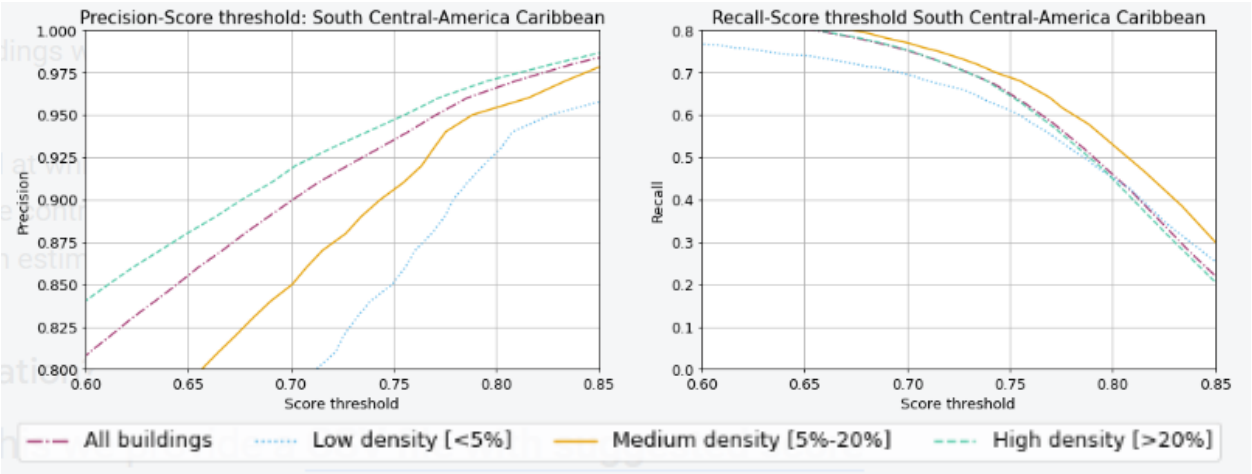


Figure 5: Precision and recall versus confidence score

The Precision is calculated as the number of correctly identified buildings (i.e., the true positives) divided by the total number of predicted buildings (i.e., the number of true positives plus the number of false positives). Recall instead is calculated as the total number of buildings correctly identified with respect to the real number of buildings.

OB provides an indication of the confidence score that allows to reach 80%, 85% and 90% of precision in the different downloadable tiles (see ***Figure 6***).

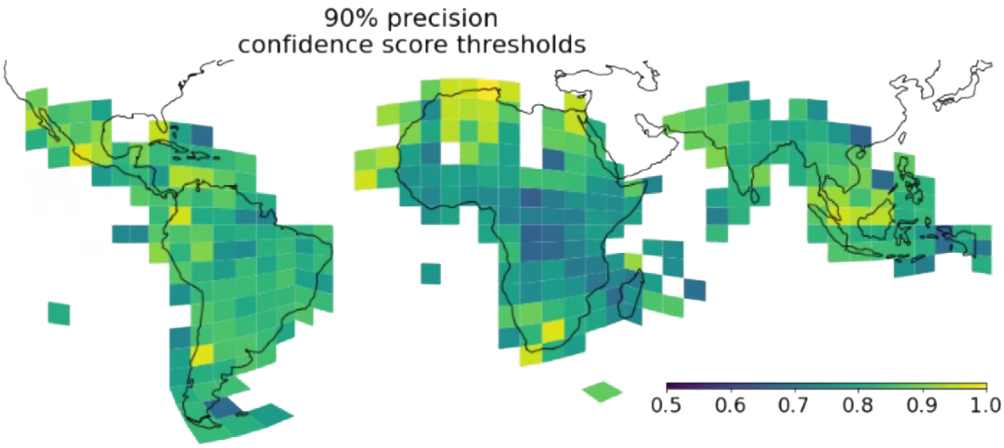


Figure 6: 90% precision confidence score levels from OB (W. Sirko, 2021)

The confidence score level recommended for use may vary depending on the specific site of interest and the nature of the analysis being conducted. Different thresholds can be applied to achieve the desired level of accuracy. For instance, as visible in ***Figure 7***, for the Eastern Cape region OB recommends setting a confidence threshold of 0.742 to achieve an accuracy level of 80%. If a higher precision is required, a threshold of 0.816 should be used to reach 90% precision. Similar adjustments can be made for other regions, aligning the confidence score with the accuracy requirements of the study.



Confidence Treshold 80% Precision	0.742
Confidence Treshold 85% Precision	0.78
Confidence Treshold 90% Precision	0.816
Building Count 80% Precision	2770015
Building Count 85% Precision	2353479
Building Count 90% Precision	1843738
Building Count	3509197
Num Samples	15702

Figure 7: Focus on the confidence threshold level in Eastern Cape

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2.1.1.1.3. Local data

If accessible, a building footprint layer specific to the site under investigation could serve as an effective and reliable solution. Local data usually provide detailed geometric representations of all existing buildings within the area of interest, enabling a more accurate analysis of building density, distribution, and characteristics. Utilizing a building footprint layer from local data allows for enhanced precision in mapping and analysis, as it directly reflects the spatial arrangement and dimensions of individual structures.

In the South African context, these data sources may be available on the municipality's official websites or directly provided by the municipal authorities.

2.1.1.2. Processing

To process the selected building footprint layers, they should be loaded into suitable GIS software to analyse their accuracy and calculate available rooftop areas. After a manual inspection, shapes that are too small to represent buildings can be filtered out.

2.1.1.3. Output

The result of this initial first step is a geospatial polygon vector layer, with features representing the shapes of building rooftops within the area of interest. Each feature includes an attribute indicating the area of the polygon. By summing the areas of all building rooftops, the Total Rooftop Area for the selected site can be obtained.

2.1.2. Step 2: Buildings Classification

The goal of this Step 1 is to classify each building within the area under analysis based on its intended use or function. This allows to have a granularity in the Technical Potential output, to detect which is the maximum PV installable on the rooftops of different users' categories.

The step involves classifying buildings as residential, commercial, industrial, public service, or others. The classification process relies on information taken from various available datasets, which provide important data regarding the existing buildings in South Africa.

2.1.2.1Input

This Step 2 requires in Input the buildings footprint vector layer obtained in Step1 and other updated layers, raster or vector, according to the availability, representing the land use in the territory. For building classification in South Africa, the recommended data sources include:

- South African National Land Cover (SANLC): Provides land cover data, essential for understanding the environmental context surrounding each building.
- Census 2011, EA-Type: Contains demographic and socio-economic data by Enumeration Area (EA), offering insights into population characteristics and the urban-rural classification of each zone.
- Census 2011, Dwell Type: Offers detailed information on dwelling types, useful for identifying residential building characteristics and classifications.

These sources could be complemented with any additional data with the same type of information. As an example, the census data should be updated with the latest available census at the time of the study.

2.1.2.1.1. South African National Land Cover (SANLC) 2022

The 20 m resolution raster of the South African National Land-Cover 2022 (SANLC 2022) dataset has been downloaded from Forestry, Fisheries and Environmental Department of Republic of South Africa website[5] (***Figure 8***). The imagery used represents the full temporal range of available imagery acquired by Sentinel 2 during the period 01 January 2022 to 31 December 2022.

Developed to support environmental monitoring, land management, and planning efforts, SANLC includes classifications for different land cover types such as urban areas, forests, grasslands, wetlands, agricultural zones, and water bodies. It classifies the South African territory in 73 classes considering dwell type, vegetation type per dwell type, land use and so on. The details of the classification are reported in ANNEX B – SOUTH AFRICAN NATIONAL LAND COVER. The layer provides a high-resolution representation of land cover, ensuring a precise analysis and a clear understanding of the spatial distribution of different land cover types. In addition, the dataset is updated periodically to reflect changes in land use and cover, ensuring that it remains a reliable source for tracking environmental changes and development.

[5] *https://egis.environment.gov.za/gis_data_downloads*

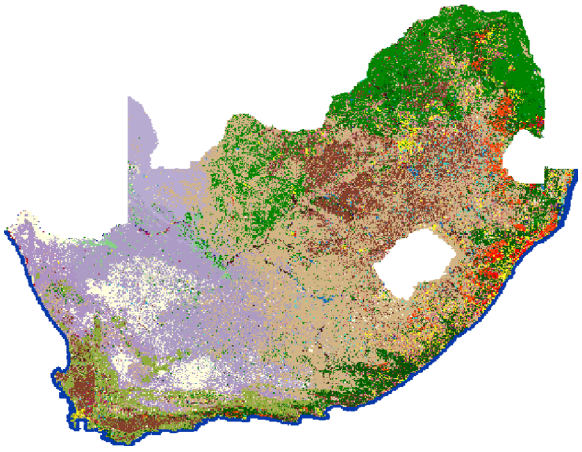


Figure 8: South African National Land Cover (SANLC) 2022

2.1.2.1.2. Census 2011, EA-Type

In the South Africa Census 2011, the term «EA Type» refers to the different types of Enumeration Areas (EAs) used for collecting and organizing census data. The EA types are categorized based on the predominant land use or characteristics of the area as follows (see ***Figure 9*** for a visual example for the area of Cape Town):

- Collective living quarters.
- Commercial.
- Farms.
- Formal residential.
- Industrial.
- Informal residential.
- Parks and recreation.
- Small holdings.
- Vacant.

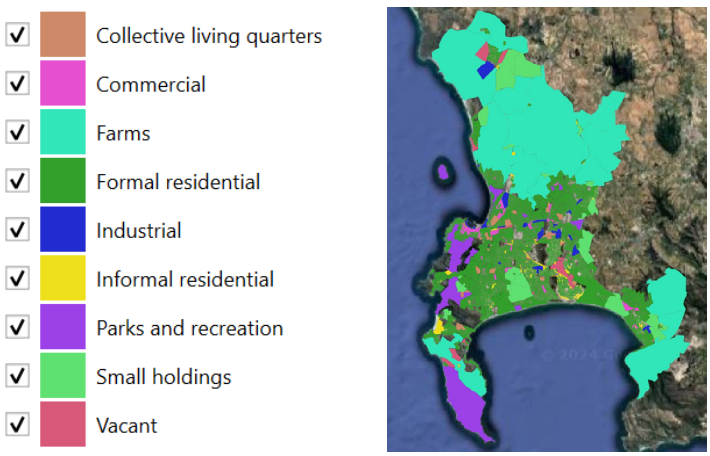


Figure 9: Cape Town municipality EA-type classification

Figure 10 provides examples of two areas with distinct classifications: one designated as an industrial area and the other as a formal residential area. The classification accuracy of these areas is evident upon comparison with Google satellite imagery, where the mapped features align precisely with the visual data.

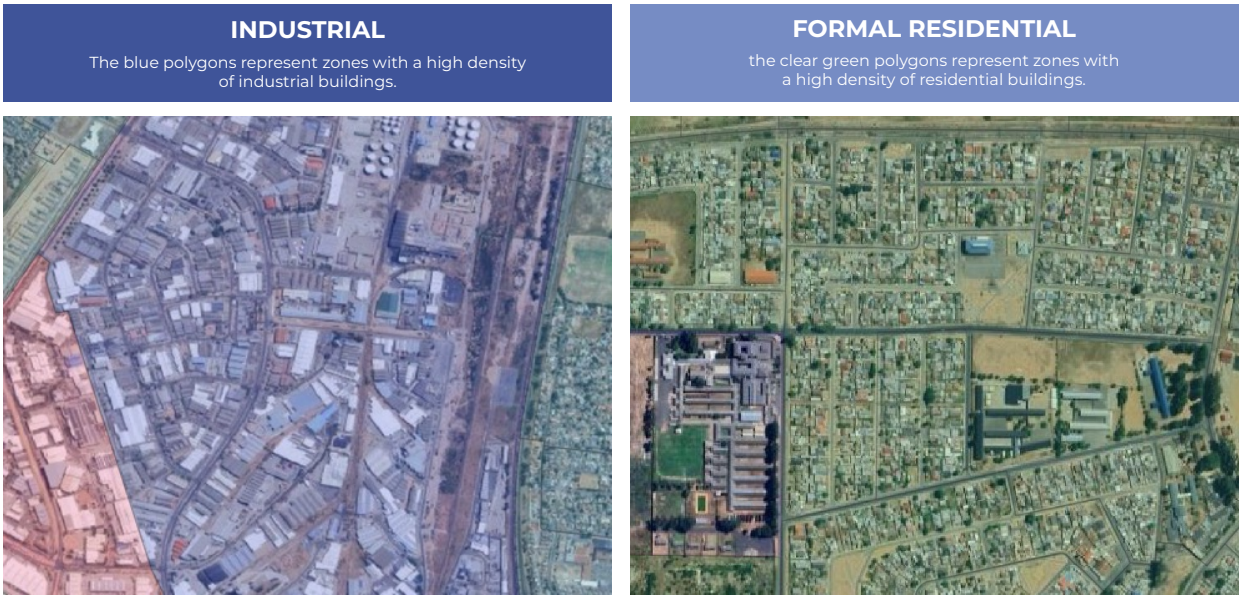


Figure 10: Industrial and Formal residential zones as per Census 2011, EA-type classification

2.1.2.1.3. Processing

The methodology for buildings classification is built on the previously described layers, which are valuable sources of data for the whole South Africa. However, the concepts and the process followed could be replicated with other vector and raster layers representing the final buildings land uses, with the possibility to increase or decrease the level of granularity of the final classification.

All the layers mentioned above have been successfully downloaded and processed, with each polygon representing a specific section of the South African territory.

While the SANLC layer covers all the territory with high accuracy, the census data have some areas that are not covered, as illustrated in ***Figure 11***, and the information dates back to 2011, thus having some gaps with the current land uses.

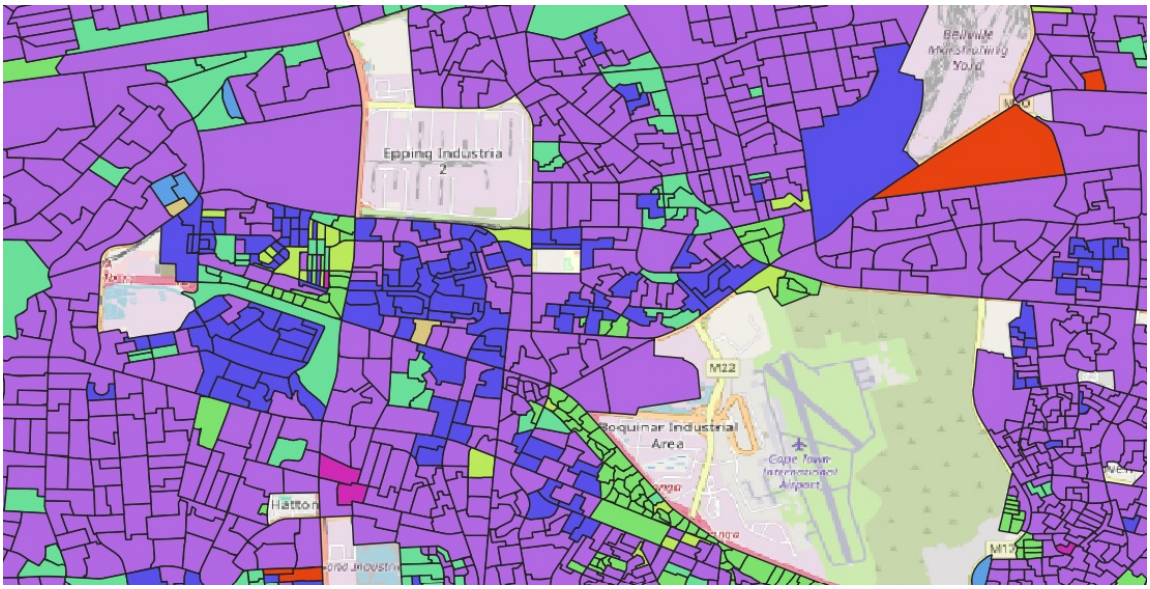


Figure 11: EA-type missing information

The methodology, therefore, prioritizes the SANLC layer, integrating and cross-referencing it with the previously listed layers to achieve comprehensive coverage across the South African landscape. This approach ensures that almost all the territory is properly represented and categorised.

More specifically, the following approach, outlined in ANNEX A-PROCEDURES is proposed:

1. *Associate SANLC Classes with Building Footprints*: Link the building footprints to the relevant SANLC classes based on their geographical proximity.
2. *Simplify and Reclassify SANLC Classes*: Reclassify the SANLC classes into categories relevant to the final users, such as Residential, Informal Settlement, Industrial, Commercial, and Agricultural.
3. *Utilize EA-Type Classification as an Alternative*: In cases where the SANLC classification includes fields irrelevant to the study's objectives (e.g., specific types of forests or rivers) or where coverage is missing, the EA-type classification will be employed to provide the necessary information. This means that for buildings located within areas classified as natural spaces, their category will be determined using census data.

With the complete set of information and the detailed layers described, it becomes feasible to categorize buildings into the following five (5) distinct classes (or more in case more granularity is needed in the study), which are considered relevant for the purpose of the study:

- *Residential*: all structures primarily used for living purposes, including single-family homes, multi-family apartment buildings, and housing complexes. It includes only formal residential units.
- *Commercial*: primarily used for business activities. This includes offices, retail stores, shopping centres, restaurants, and others engaged in commercial operations.
- *Industrial*: dedicated to industrial activities, such as factories, warehouses, manufacturing plants, and distribution centres.

- *Informal residential*: such as shacks or informal settlements.
- *Agricultural*: structures related to agricultural activities. It includes barns, silos, and farmhouses. These buildings support various agricultural operations, such as crop production, livestock housing, and equipment storage.

It is recommended to exclude informal residential buildings from the analysis, as they are typically deemed unsuitable for photovoltaic (PV) installations due to structural limitations, lack of access to necessary infrastructure, and irregular construction practices.

Regarding agricultural zones, their inclusion or exclusion should be guided by the specific focus of the study. If agricultural areas are not relevant to the research objectives, they may be excluded. However, if they warrant further examination—such as large farm buildings or barns with potential for PV installation—these areas can either be integrated into one of the existing categories or treated as a separate category.

By adapting the approach in this manner, the analysis can remain flexible and tailored to meet the objectives and constraints of the study effectively.

2.1.2.1.4. Output

The output from Step 2 is the building footprint layer enriched with additional attributes related to the buildings' final use. This enhancement enables the computation of the total rooftop area for each user category.

2.1.3. Step 3: Usable Rooftop Area Estimation

After determining the Total Rooftop Area available at the chosen site in Step 1 of the methodology, the goal of this analysis phase is to refine that estimate by identifying the Suitable Rooftop Area for PV installations. *The Suitable Rooftop Area* is the portion of the total area that remains technically viable for solar PV systems, after considering various practical, real-world factors:

1. *Shading* is a major factor that can significantly reduce the rooftop area suitable for solar.
2. *Additionally, rooftop slope* influences how effectively solar panels capture sunlight, as overly steep roofs may hinder energy collection.
3. The third key factor is the buildings' *orientation*, which plays a vital role in how much sunlight a rooftop can receive.

Finally, the Suitable Rooftop Area must be further refined to identify the Usable Rooftop Area for PV systems by considering essential spacing requirements to avoid shading, maintenance access, and obstructions on the rooftop, such as air conditioning units, chimneys, and ventilation systems.



Figure 12: Usable Rooftop Area calculation flowchart

2.1.3.1. Input

The Step 3 uses as input the buildings footprint layer obtained in Step 1, as well as the Digital Surface Model (DSM) raster layer with at least 1m resolution. The DSM is a 3D representation of the Earth's surface that includes all natural and man-made features, such as buildings, trees, and other structures. DSMs are often used in Geographic Information Systems (GIS) for urban planning, environmental studies, and assessing the potential for solar energy installations on rooftops. The raster pixels have associated the values of the altitude including buildings. Having high enough resolution, it is hence possible to compute the slope of the rooftops, as well as the aspect and shading as detailed later.

In case the DSM is not available, average coefficients for determining the slope, shading and aspects of rooftops could be used, as detailed in the procedure (ANNEX A-PROCEDURES).



Figure 13: Digital Surface Model (DSM) visualization on ArcGIS

Processing

ArcGIS software is utilized to determine the Suitable Rooftop Area for solar installations starting from the DSM and the buildings footprint layer. ArcGIS is a powerful GIS software developed by Esri that allows users to visualize, analyse, and interpret spatial data.

The Suitable Rooftop Area is determined by subtracting from the Total Rooftop Area the sections that are shaded, excessively steep, or poorly oriented to receive adequate solar radiation.

a) Shadows

As first step, the ArcGIS Hillshade function is used to produce a grayscale 3D representation of the terrain surface, with the sun's relative position considered for shading the image. This function is used to evaluate the shading effects caused by various features in the environment. Specifically, it is used to assess how shadows from buildings interact with one another, which is essential for determining potential impacts on solar access for neighbouring structures. For example, in densely built environments, one building may cast significant shadows on adjacent rooftops, which could affect the potential for solar panel installations or the overall energy efficiency of the neighbouring buildings. Beyond urban structures, the Hillshade function is also utilized to evaluate shadows cast by natural features, such as mountains, hills, and trees. These natural obstructions can significantly affect sunlight exposure and solar radiation levels in a given area.

Our methodology consists in choosing at least four representative days (one per season) and to investigate hours from sunrise to sunset per each day. Sun azimuth and altitude for the chosen days and hours could be downloaded from open-source websites (SunEarthTools.com[6] is advised). A visualization of the result of the Hillshade function is reported in ***Figure 14***.

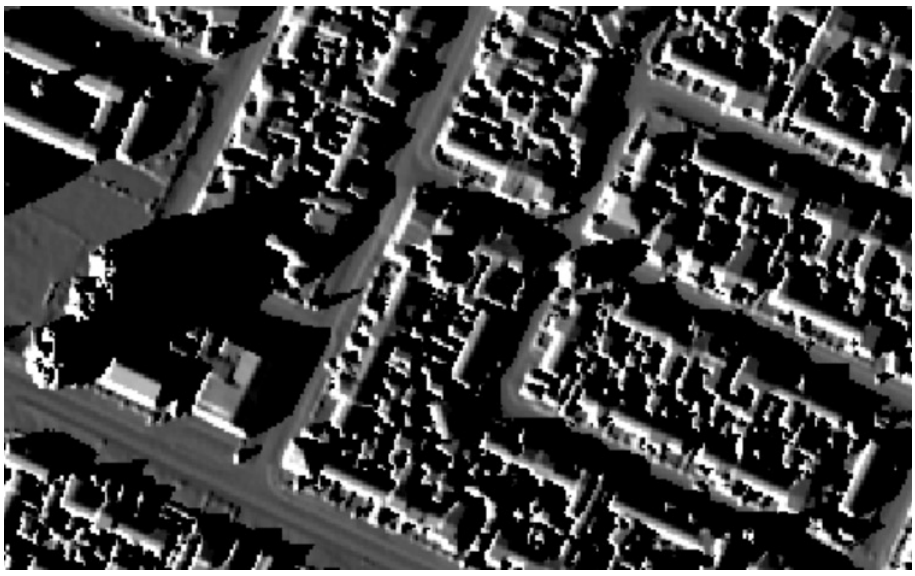


Figure 14: Hillshade function result

[6] *https://www.sunearthtools.com/*

b) Slope

As a second step, the ArcGIS Slope tool is used to identify the steepness of each cell of the input DSM raster, measured in degrees. This tool is critical in terrain analysis as it provides precise information about the rate of elevation change across a surface, helping to identify areas with varying degrees of slope. Each cell in the resulting layer contains a slope value ranging from 0 to 90 degrees. The lighter colours represent steeper slopes while darker colours represent milder slopes.

In the analysis of PV Technical Potential, the slope of rooftops is a crucial factor that influences the efficiency and performance of solar panels. The slope, or tilt angle, of a surface determines how much sunlight the surface receives and how efficiently the solar panels can convert sunlight into electricity. For optimal energy generation, solar panels need to be installed at an angle that maximizes their exposure to sunlight. On flat rooftops, i.e. the ones with a slope close to 0, panels can be installed at their optimal angle, while on tilted rooftops panels are normally mounted at the same inclination of the roof pitch.

A visualization of the result of the Slope function is reported in ***Figure 15***.

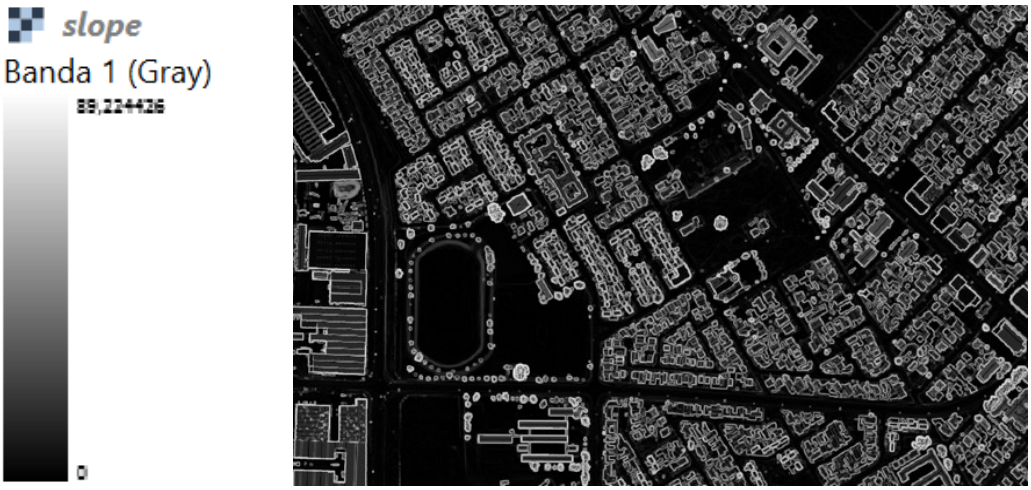


Figure 15: Slope function results

c) Orientation

At the end, to determine the rooftop orientation, an aspect raster layer is created using the ArcGIS Aspect tool. This tool is essential for identifying the direction that each downhill slope or surface faces, which is a critical factor in assessing the solar energy potential of rooftops. The tool assigns values ranging from 0° to 360°, allowing for precise determination of the direction the surface faces. The key orientations are defined as follows:

- **0°** represents **north orientation**.
- **90°** represents **east orientation**.
- **180°** represents **south orientation**.
- **270°** represents **west orientation**.

A visualization of the result of the Aspect function for determining the Orientation is reported in ***Figure 16***.



Figure 16: Aspect function results

d) Filter

After the definition of shadows, slope and orientation of each pixel, the data are filtered to exclude rooftops that are unsuitable for solar panel installation due to factors such as shading, structural constraints, or incorrect orientation. To identify suitable rooftops for PV installations, three criteria needed to be considered:

1. *Shadows Filter*: For rooftops to be viable for PV installations, they should receive ample sunlight. An acceptable threshold is that no more than 20% of the rooftop is shaded during the day or year, ensuring sufficient sunlight exposure. Rooftops with up to 50% shading may still support PV installations, though efficiency may be reduced.
2. *Slope Filter*: Ideal rooftops have a slope within a specific range, as steeper slopes receive less sunlight. Flat rooftops are suitable for rooftop PV installed on support structure, which could be tilted at the optimal angle. A rooftop slope of 15–40 degrees is optimal for PV installations, as it maximizes sunlight exposure year-round with minimal adjustment. While slopes between 40–60 degrees can still be feasible depending on location and structure, slopes over 60 degrees are typically unsuitable for efficient PV installation.
3. *Orientation Filter*: Orientation is key to maximizing solar capture. In the southern hemisphere, the best orientation is north-facing, which optimizes sunlight exposure throughout the year. Typically, south-east to south-west orientations are excluded for tilted surfaces, whereas all directions may be considered suitable on flat rooftops.

The filters are applied to the high-resolution raster layer to obtain a binary layer with 1s associated to the *suitable pixels*, i.e. the ones respecting the three above conditions, and 0s to the rests.

Thanks to the ArcGIS Zonal Statistics tool the raster of suitable pixels is then associated to the buildings footprint layer to obtain, for each building, the total number of pixels and the number of *suitable pixels*.

The Suitable Rooftop Area is hence computed for each building:

$$Suitable\ Rooftop\ Area = Total\ Rooftop\ Area \cdot \frac{\#\ suitable\ pixels}{\#\ total\ pixels}$$

Summing up the Suitable Rooftop Area for each individual rooftop is hence possible to find the total Suitable Rooftop Area in the site of interest.

In addition, useful information retrieved from this step of the methodology are:

- ***tilt***: the percentage of tilted rooftop area over the total rooftop area.
- ***flat***: the percentage of flat rooftop area over the total rooftop area.
- ***slope***: the average slope of tilted rooftops.
- $coeff_{suit_tilt}$: the percentage of suitable over the total rooftop area of tilted rooftops.
- $coeff_{suit_flat}$: the percentage of suitable over the total rooftop area of flat rooftops.

e) Usable Rooftop Area

The total Suitable Rooftop Area offers an initial estimate of the space available for solar PV installations, factoring in reductions due to roof shading, slope, and orientation. However, further adjustments are required to optimize solar panel deployment, taking into account essential spacing between modules to prevent shading, access space for maintenance, and rooftop obstructions such as air conditioning units, chimneys, and ventilation systems.

To consider this additional surface reduction, a *Usable Area Coeff* ($coeff_{usab}$) can be used for differentiating flat and tilted rooftops. Even though flat rooftops have a higher potential for PV coverage, a 70% of the total available area can be reasonably used for panel installation. Similarly, for tilted rooftops, only approximately 73%[7] of the total suitable area can be used effectively. The suggested coefficients are selected from (Robert Margolis, 2017) and (Boyd, 2019) respectively and they should be considered as recommendations subject to change based on the context and available data.

This results in a final estimation of the total *Usable Rooftop Area* required for solar installations.

For flat rooftops:

$$Usable\ Rooftop\ Area_{flat} = Suitable\ Rooftop\ Area_{flat} \cdot coeff_{usab,flat}$$

For tilted rooftops:

$$Usable\ Rooftop\ Area_{tilted} = \frac{Suitable\ Rooftop\ Area_{tilt} \cdot coeff_{usab,tilt}}{\cos(slope)}$$

Summing up the *Usable Rooftop Area* for each individual rooftop is hence possible to find the *total Usable Rooftop Area* in the site of interest.

[7] *This coefficient was computed in (Boyd, 2019) by calculating the number of panels which could fit on 10 randomly selected rooftops. The authors used QGIS software to manually evaluate how a rectangular grid of modules could fit on different irregular rooftop shapes.*

The Digital Surface Model (DSM) with high resolution is not always easily available. In this case, average coefficients and standard data from literature could be used to achieve the photovoltaic Technical Potential assessment. In particular, it is possible to extend data and coefficients obtained from the POF (Section 4) for the municipality of Cape Town to the entire South African territory.

2.1.3.2. Output

The output of this procedure is a building footprint layer, already classified in Step 2, with the Usable Rooftop Area for each building included as an additional attribute.

2.1.4. Step 4: PV Technical Potential Estimation

The last step is the evaluation of the photovoltaic Technical Potential in terms of total installable capacity [GW] in the study area. The capacity is detailed per user category, according to the classification performed in Step 2.

This final step can be conducted in Excel by converting the building footprint layer—with classification and Usable Rooftop Area—into a table. Additionally, data on PV module land occupation, sourced from commercial datasheets of the most common PV manufacturers in South Africa, is required.

The PV capacity for each rooftop is calculated as follows:

- *Select Candidate PV Model*: a reference module for rooftop PV installations in South Africa should be selected, it could be either a commonly installed commercial module or a state-of-the-art standard. Knowing the modules dimensions and the peak power, the occupation factor (m^2/kW) can be determined. Monofacial modules, with sizes ranging 400W-500 W and efficiencies of 20%-22% are common choices for rooftop PV installations.
- *Calculate total PV Capacity [kW]*: For each building, the PV capacity is calculated as the ratio of the building's Usable Area to the PV modules' occupation factor. The total PV capacity for the selected area is then the sum of PV capacities for each building in the zone.
- *Assign Maximum PV Capacity per User*: Based on the classification of each building into the different users' categories performed in Step 2, the total maximum PV capacity for Residential, Commercial and Industrial customers can be computed. Dividing the PV capacity per the number of users of each category it is hence possible to compute the maximum PV capacity per user.

This approach enables a detailed, user-specific estimation of PV Technical Potential across the study area.

2.2. ECONOMICALLY VIABLE POTENTIAL

The goal of the second part of the methodology is to identify which sub portion of the PV Technical Potential would actually be economically viable for installations, considering the perspective of final users, whose goal is to save money and improve the reliability of the electricity supply.

The economic viable potential refers to the calculation of the PV and battery capacities that customers may be willing to install to reach the economic optimum or satisfy reliability and environmental requirements, given a set of input data and constraints regarding energy balances, technical characteristics, costs, tariffs and available space.

Differently from the technical analysis, the Economically Viable Potential represents a more economically realistic measure of the PV and battery capacity that the customers would be willing to install, constrained by the maximum available space. Like the Technical Potential, it depends on the available solar resource and usable area for PV deployment, but it also considers the load demand, the grid availability, the electricity costs and tariffs as well as the investment and O&M costs related to the PV and battery systems.

After a section devoted to the literature review on models and approach to optimise PV-BESS systems, this section outlines the methodology to assess the Economically Viable Potential in a region for which all the necessary input data are available, whereas later in the «Proof of Concept» section the Cape Town municipality is focused on performing a demonstration of the presented methodology.

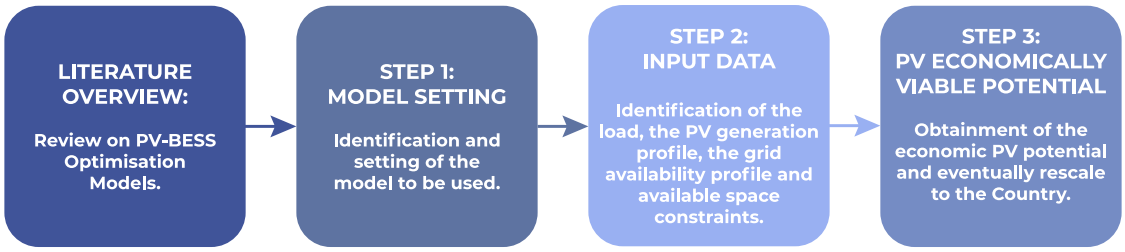


Figure 17: PV Economically Viable Potential flowchart

2.2.1. Overview on PV-BESS Optimisation Models

This section illustrates the methods and strategies to size small-scale PV and BESS systems in rooftop and community (e.g., microgrids) applications. They range from intuitive/simplified methods, – based on logical considerations and sizing criteria, – to rigorous mathematical models, aimed at optimizing the system based on simulations and numerical methods.

The goal of this section is to provide a rationale for the selection of the appropriate model for implementing the proposed Methodology.

2.2.1.1Intuitive Methods

The ***intuitive methods*** are methodologies using simplified calculations and designer experience to obtain a rough estimation of the optimal solution. According to Mobi (Mobi Mathew, 2021), there exists a set of *deterministic methods* that can be considered a subset of the intuitive methods, as the system size is determined from the highest or average monthly load demand.

As an example, Bhuiyan (M.M.H. Bhuiyan, 2002) estimates the optimal PV array size and storage capacity for a stand-alone system with a simplified approach based on data as the hourly load demand during a typical year, the mean daily irradiation and other meteorological characteristics of the site, and the characteristics of the PV modules and the battery. In particular, the battery capacity is sized to cover the daily total demand multiplied per the number of days of autonomy (usually ranging from 2 to 3 days), and then divided by a

factor accounting for the maximum Depth of Discharge (DOD) of the battery and by another factor representing the efficiency depending on the temperature. On the other hand, the PV array is sized in a conservative way to cover the load during the days of minimum insolation and calculated more in detail using equations involving the modules characteristics.

Differently from Bhuiyan, another intuitive method is presented in Kaushika (N.D. Kaushika, 2005), where the PV size is dimensioned to cover the daily mean load, in a less conservative way with respect to the first example.

The CIGRE Rural Electrification Technical Brochure (WG C6.38) (CIGRE, 2021) reports an example of a simple methodology for stand-alone PV systems in rural context. In this case, it is considered both the mean daily load demand and the peak load. The size of the storage system is determined as the one able to both cover the daily energy demand for a minimum number of days of autonomy and the peak load during nighttime hours. The PV size is computed as the one able generate the daily energy needed by the system to work, during the month of minimum irradiation. The energy is given by the sum of the daily load energy consumption and energy to recharge the batteries during the recovery time from minimum state of charge.

Table 1: Summary of intuitive methods for PV and BESS sizing

Source	Input data	PV sizing logic	BESS sizing logic
(M.M.H. Bhuiyan, 2002)	Average daily load, PV and BESS characteristics, irradiation and site parameters.	Cover load during minimum insolation.	Satisfy minimum days of autonomy.
(N.D. Kaushika, 2005)	Average daily load, PV and BESS characteristics, irradiation and site parameters.	Cover the daily mean load.	Satisfy minimum days of autonomy.
(CIGRE, 2021)	Average daily load, peak load, PV and BESS characteristics, irradiation and site parameters.	Cover the daily mean load and the energy to recharge the batteries during the month with minimum solar irradiation.	Satisfy peak load and the energy consumption for minimum days of autonomy.

2.2.1.2. Mathematical Models

According to Mobi (Mobi Mathew, 2021), the definition of a model to optimize a rooftop PV-based microgrid refers to the formulation of a sizing optimization problem considering, first, a set of input data, i.e. load demand profile, available resources, budget. Then, a set of variables to be optimized is considered:

$$x$$

that, in the context of this project, are usually the rooftop PV and storage capacity to install.

One or more objective functions are then defined:

$$\boldsymbol{min(f(x))\ \ or\ max(f(x))}$$

Lastly, technical, economic, environmental and reliability constraints are formulated:

$$\boldsymbol{x \in range(x)}$$

$$\boldsymbol{g(x)=0}$$

$$\boldsymbol{h(x)<0}$$

Common objectives can be of economic nature, such as the minimization of the Net Present Cost (NPC) of all components of the project, of environmental nature, such as the minimization of the total or specific CO_2 emissions or, lastly, of reliability nature, such as minimizing the loss of load probability or other indices. The most common approach is to select the minimization of the NPC as single-objective function of the optimization problems.

Moreover, the literature describes a way to consider more than one single objective function, that is the *multi objective optimization method*: this approach balances various objective functions like cost, reliability and environmental impact to find an optimal solution, by combining them in a single function and obtaining a tradeoff among all of them. There are three main methods to define a multi-objective model:

1. The first of which is the "global criterion method, where the single objective functions are combined in a single equation that measures the distance of each objective from their optimal value:

$$Obj = opt \sum_{i=1}^{k} \frac{f_i^0 - f_i(x)}{f_i^0}$$

   where $\boldsymbol{f_i^0}$ is the optimal value of the single objective function $\boldsymbol{f_i(x)}$ calculated by singularly considering the function $\boldsymbol{i}$.

2. Another common methodology is the **weighted sum method**, that combines the single objective functions in a single function by summing the weighted normalized objectives:

$$Obj = opt \sum_{i=1}^{k} \alpha_i \cdot \frac{f_i(x)}{f_i^0}$$

3. Lastly, the **ε-constrained method** requires no aggregation of functions but rather considers and optimizes only one objective function f_i while constraining the others f_j with upper or lower bounds:

$$Obj = opt\big(f_i(x)\big), \quad f_j < \varepsilon_j \quad with\ j \neq i$$

As an example, in the described case study Mobi proposes a problem where a PV-based microgrid for a typical hospital in Dhaka, Bangladesh, has been designed with the software HOMER, by relying on the minimum NPC objective function in the optimization, and subject of different scenarios of constraints that attempt to singularly minimize the Cost of Energy, CO2 emission, unmet electric load, and loss of energy probability, as well as maximize the use of renewable energy.

2.2.1.2.1. Analytical Methods

The first category of mathematical is the set of **analytical methods**: this kind of methodologies require formulating analytical equations and relations among the variables and parameters of the problem and solving it for the defined objective function, i.e. usually the minimum NPC or other cost or environmental objects. According to Mobi 2021, *the linear & non-linear programming methods* are the most common analytical methods and involve the solving for an objective function while ensuring the problem constraints.

An example of analytical method is represented by (Iflah Javeed, 2021). The article investigates a comparative study for practical optimal sizing of rooftop PV systems by considering two system configurations, PV-only and PV-BESS, and minimizes the Net Present Cost of electricity for four options of electricity rates. A practical model is developed by considering basic energy balance equations involving grid constraints, load demand and daily supply of electricity. Similarly, (Koko, 2022) develops an optimal power flow control model to determine the optimal battery size, through the use of MATLAB optimization solver called *linprog* and the consideration of different battery sizes.

As an example, the open-source tool *MicroGridsPy* by Politecnico di Milano (Nicolo Stevanato, 2020) uses Linear Programming to simulate and optimize micro grids in rural areas including a various set of input parameters better described in the next chapters.

2.2.1.2.2. Heuristic Optimisation

The third type are the **Heuristic Optimisation methods**, which are methods that simulate natural processes and behaviours to find the optimal solution. Some commonly used heuristic methods for microgrid optimization are Genetic Algorithm (GA) – based on Charles Darwin's theory of natural evolution and reflects the process of natural selection where the fittest individuals are selected for "reproduction" in order to produce offspring of the next generation until the fittest individual (i.e. the optimal solution) is found –, Particle Swarm Optimization (PSO) – it mimics the movement of organisms in a bird flock and it is based on repeating a process until an optimal solution is found –, Simulated Annealing (SA) – it is inspired by the annealing process in metallurgy. It allows the algorithm to occasionally accept worse solutions, helping it escape local optima –, and Hybrid Heuristic Approaches, that combines the previous methods to leverage their strengths.

As an example, the common commercial softwares *iHOGA* (improved Hybrid Optimization by Genetic Algorithms) and *MHOGA* (MegaWatt Hybrid Optimization by Genetic Algorithms) uses genetic algorithms for the simulation and optimization of electric power generation systems based on renewable energies. Another common commercial software using heuristic algorithms is *HOMER* (Hybrid Optimization Model for Multiple Energy Resources), that simulates the operation of a hybrid microgrid for an entire year, in time steps from one minute to one hour, and will consider a viable system for all possible combinations of the considered equipment.

Also, in Merei (Ghada Merei, 2013) a Genetic Algorithm is used, where the fitness (objective) function is the total cost, and the optimal value of each parameter is chosen within the defined upper and lower boundaries.

2.2.2. Step 1: Model Setting

To perform the economically viable potential, the open-source software MicroGridsPy by Politecnico di Milano was selected and adapted to meet the project specifications and needs. Quoting the official documentation page, *"MicroGridsPy is a Linear Programming-based, bottom-up, open-source optimization model, running on Pyomo, a Python library used to model optimization problems, whose primary goal is to offer an open-source approach to the issue of energy scaling and dispatch in micro grids in remote locations"*[8] . It was firstly developed in 2016 by University of Liege and the code is freely available on GitHub[9].

The model was created for optimizing the sizing of renewable energy sources, generators and batteries in a microgrids with a defined load demand profile, but its flexibility makes it adaptable to a wide range of problems. Within this methodology, the tool is used to optimize the size of PV and batteries for single users connected to the national grid.

Figure 18 shows the flowchart of the model: taking as inputs the load demand, the generators and renewable sources characteristics, the grid availability profile and other technical-economic features, through the user interface the model optimization parameters can be selected by the user and the output results are returned, i.e. the total project cost, the CO2 emissions and the grid usage.

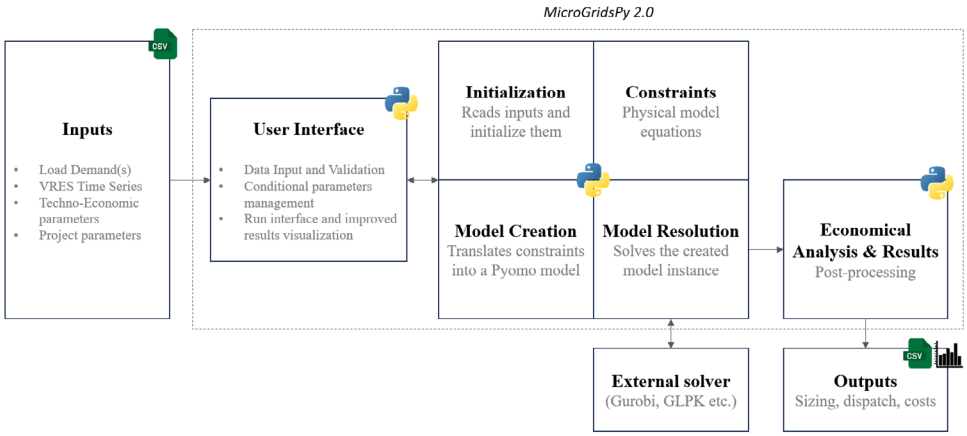


Figure 18: MicroGridsPy model flowchart

The *MicroGridsPy* optimization model is structured to determine the most cost-effective combination of installed capacities for renewable energy sources, batteries and generators, specifying first the objective function to consider among:

- Net Present Cost minimization, that represents the total cost of the microgrid over its entire lifespan, discounted to the present value.

$$NPC = C_{investment} + C_{O\&M} - Salvage\ value$$

[8] *https://microgridspy-docs.readthedocs.io/en/latest/*
[9] *https://github.com/SESAM-Polimi/MicroGridsPy-SESAM*

- Total Variable Cost minimization, that includes the costs of operation and maintenance of the energy production facilities, the cost of fuel for generators, and any other costs that are not fixed.

$$TVC = C_{O\&M}$$

Eventually, the tool also offers the possibility to perform a multi-objective optimization, taking into account both costs and CO2 emissions, in formula:

$$Emissions_{CO_2} = Emissions_{RES} + Emissions_{Fuel} + Emissions_{BESS} + Emissions_{Grid}$$

In particular, this option is able to build a Pareto Curve representing various trade-off solutions between Net Present Cost and emissions. The Pareto optimal front represents the set solutions where no objective can be improved without worsening the other. The users can select the number of Pareto points to analyse, allowing them to explore the spectrum of solutions from minimizing emissions to minimizing costs. For the decision makers, this is useful to visualize how different objectives support or conflict with one another, as it provides a comprehensive view of the trade-offs involved.

This is achieved through a series of optimization steps:

- Single-objective minimization: first, each objective is singularly optimized to establish a baseline value.
- Extremes calculation: the maximum feasible values for NPC and CO_2 emissions, which are the values corresponding to the minimum of CO_2 and NPC respectively, are calculated.
- Pareto optimal front: next, costs are iteratively minimized while constraining CO_2 emissions to a series of values, from their minimum calculated one up to the maximum by increasing the constraint in each step, allowing to generate a set of NPC and CO_2 emissions pairs that form the Pareto optimal front.

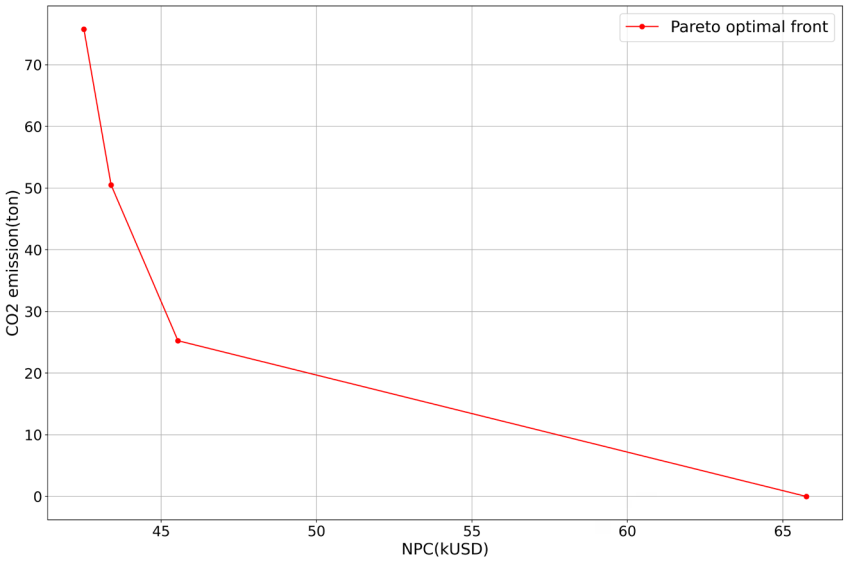


Figure 19: Example of Pareto front

For the purposes of the present project, the objective function selected to run the simulations is the minimization of the Net Present Cost.

The model is based on an energy balance that must be satisfied at any given moment:

$$E_{load}(t) = \sum_i E_{RES}(i,t) + \sum_i E_{GEN}(i,t) + E^{+}_{Grid}(t) - E^{-}_{Grid}(t) + E^{-}_{BESS}(t) - E^{+}_{BESS}(t) + Lost\ load(t) - Curtailment(t)$$

where:

- $E_{load}(t)$ is the load demand at a given time t,
- $E_{RES}(i,t)$ is the electricity generation of RES source i at time t,
- $E_{GEN}(i,t)$ is the electricity generation of non-RES source i at time t,
- $E^{+}_{Grid}(t)$ is the electricity coming from the grid,
- $E^{-}_{Grid}(t)$ is the electricity fed to the grid,
- $E^{-}_{BESS}(t)$ is the electricity discharged from the battery,
- E^{+}_{BESS} (t) is the electricity charged to the battery,
- $Lost\ load(t)$ is the load that couldn't be satisfied, and
- $Curtailment(t)$ is the excess generated electricity.

A graphical scheme of the energy balance is also given in *Figure 20*.

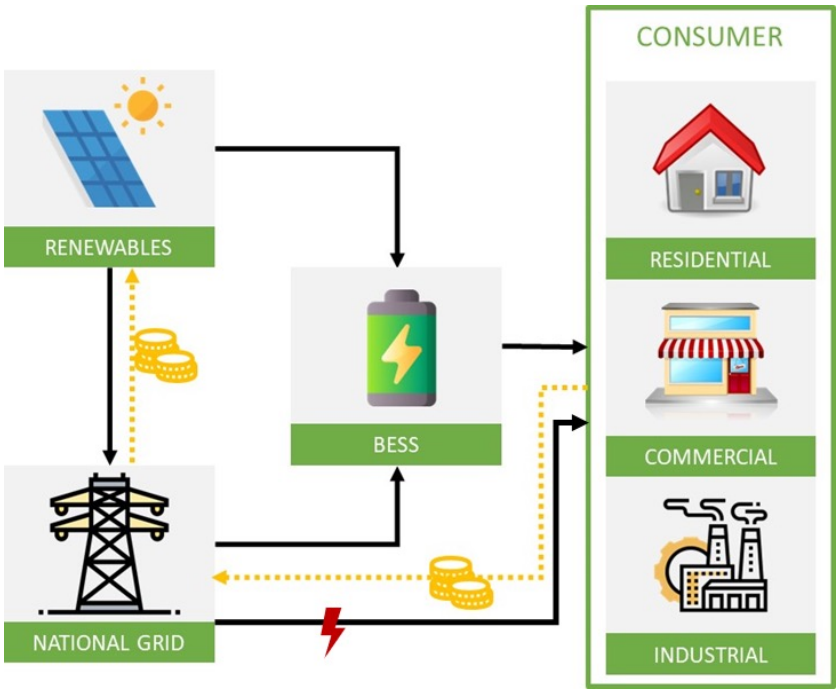


Figure 20: Energy and economic flows

The tool allows also to consider the potential unavailability of the grid – represented with the symbol ⚡ in the scheme above –, which can be used to represent the load shedding hours. This reliability feature model can either estimate endogenously a grid availability profile based on Weibull distributions given the average number of outages in a year and the average outages duration, or take an hourly input profile, with 0 if grid is unavailable and 1 if available. The latter is the option selected for the project.

For other equations and details on the MicroGridsPy mathematical formulation, please refer to the online documentation[10].

2.2.3. Step 2: Input Data Definition

The MicroGridsPy models primarily rely on Python scripts (.py files) for their definition, along with .csv files for time series data and .dat files for input parameters. All these input files are organized within a directory named "Inputs", which typically has the layout shown below.

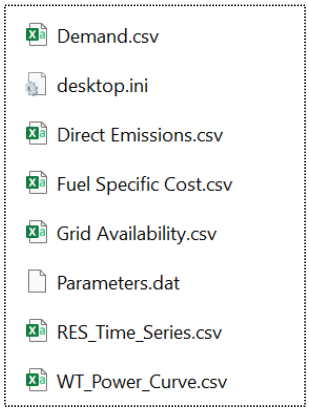


Figure 21: Model inputs

In particular:

- *Parameters.dat*: this file contains the primary configuration and parameters of the model, including the system characteristics, economic parameters, and technology-specific data.
- *Demand.csv*: this file holds the hourly profile of the electricity demand.
- *RES_Time_Series.csv*: it contains the renewable energy sources' generation hourly profiles.
- *Grid Availability.csv*: it provides data on grid availability, represented as a matrix of 0s and 1s, where availability is 0 when the grid does not allow the electricity flow and 1 when it flows normally, as an hourly profile.
- *Direct Emissions.csv*: it contains data related to emissions directly associated with the energy system's operation (not used in the model).
- *WT Power_Curve.csv*: it details the power curve of wind turbines, showing the relationship between wind speed and generated power (not used in the model).

[10] *https://microgridspy-docs.readthedocs.io/en/latest/*

In the Proof-of-Concept (POC), presented in Section 4, the numerical values selected for the identified case study are presented. Those could be retrieved by literature, commercial datasheets, stakeholder interviews open-source databases or historical statistics. The data will need to be specific for each type of user that will be modelled and adapted to the South African context.

To obtain a PV generation profile regarding the file *RES_Time_Series.csv*, a zone within the target area that represents the average solar irradiation needs to be identified. The following steps are necessary:

1. Download Global Horizontal Irradiance (GHI) from a reliable source such as the Global Solar Atlas[11] or a similar database that provides accurate solar radiation information for the area of interest. This data should cover the entire geographic area under consideration, such as a municipality or a small region.
2. Analyse the GHI data to determine the range of irradiation values across different zones: identify the minimum GHI value to establish a baseline for assessing the suitability of various zones for rooftop PV installations. Usually, a range between 1,400 to 2,000 kWh/m² per year is typically considered optimal for PV installations. Locations within this range have good solar exposure, making solar panels highly efficient and cost-effective. Eventually remove zones with extremely low GHI.
3. At this point, calculate the mean GHI value for the area under study. This average will serve as a benchmark to identify zones that are representative of the typical solar irradiation conditions in the study are. Note that the lower is the extension of the area, the more precise and representative will be its average GHI value as benchmark. Otherwise, it is suggested to divide the study area in more than one representative zones, in case the GHI varies significantly within the whole study area.
4. Identify a point or zone on the map that approximates the mean GHI value as closely as possible. This point will serve as a reference location for further analysis, as it represents average solar conditions within the area.
5. Use tools such as PVGIS (Photovoltaic Geographical Information System)[12] or similar software to download detailed hourly solar profiles for the selected point. Obtain data that covers various configurations and scenarios to determine the potential for solar energy generation.

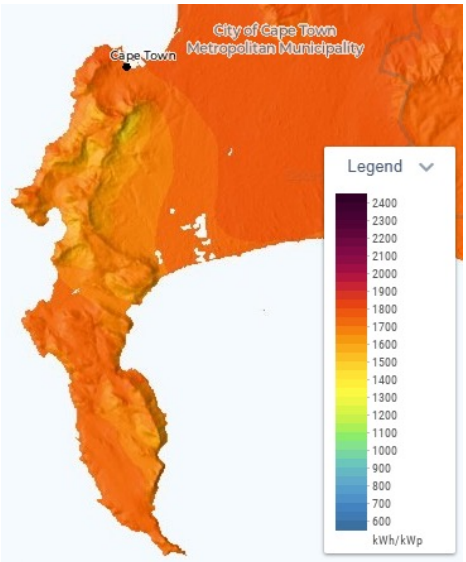


Figure 22: South Africa in Global Solar Atlas

[11] *https://globalsolaratlas.info/*
[12] *https://re.jrc.ec.europa.eu/pvg_tools/en/*

2.2.4. Step 3: PV Economically Viable Potential Estimation

The MicroGridsPy simulations are run for any possible configuration of PV-BESS system (e.g., *The MicroGridsPy* simulations are run for any possible configuration of PV-BESS system (e.g., standalone, community, grid-connected, isolated, …) – in the POC (see section 4), the identified type of user for this study are standalone installations of grid-connected Residential, Commercial, and Industrial PV-BESS systems – to obtain the following results:

1. Installed capacities:
   - Solar PV installed capacity.
   - Battery installed capacity.
2. System costs:
   - Net Present Cost (NPC).
   - Total actualized Investment Cost.
   - Total actualized Operation Cost.
   - Total actualized Electricity Selling Revenues.
   - Salvage Value.
   - LCOE.
3. Energy balances:
   - Average renewable penetration per year.
   - Average battery usage per year.
   - Average national grid usage per year.
   - Average curtailment per year.
   - Renewables Land Use.
4. Hourly profiles:
   - PV production.
   - PV curtailment.
   - PV energy sold to the grid and energy bought from the grid.
   - BESS charge and discharge.

3. DATA COLLECTION

NTCSA indicated Western Cape as the Province of interest for developing the POC analysis, being it a supply area subject to grid constraints and characterized by high PV installations. To focus the analysis on a specific area, CESI and NTCSA agreed to use the municipality of Cape Town as the boundary for the study.

The data collection process has involved several stakeholders, with dedicated forms and surveys, to capture the perspectives and information available from the relevant South African entities operating in the rooftop PV sector, i.e.:

- NTCSA.
- COCT.

RES4Africa facilitated the coordination with the stakeholders for data and information exchange. To complement the information received, CESI also downloaded public information available online.

3.1. INFORMATION REQUEST TO NTCSA AND COCT

The initial request of data from RES4Africa and the relevant South African entities occurred in June 2024 and followed two main phases:

1. A preliminary discussion of the data needs was introduced during the Kick-off-Meeting in June 2024 with the representatives of RES4Africa and NTCSA.
2. The data request form was delivered.

In particular, the data request covered the following items:

- *Rooftop data*: this information is fundamental to accomplishing the task on the Technical Potential analysis. More specifically, data are needed to identify the share of buildings with flat rooftops, the average slope for tilted rooftops and the share of available rooftop area for PV installations.
- *Buildings data*: this information is needed to assess the number of buildings disaggregated by function (residential, commercial, industrial) and municipality.
- *GIS Data*: this information is needed to derive some additional informative layers on the existing buildings (e.g., functions such as residential, commercial/industrial, or public service, etc.), the socioeconomic, socio-political, and demographic attributes of the different municipalities, and the DSM of the country.
- *Load and production data*: this information is needed to derive load and production data from existing conventional and Variable Renewable Energy Resource (V-RES) plants, the updated total installed capacity, and the technical and financial performance of existing rooftop PV and BESS.
- *Reliability data*: information about the service delivery indicators, load shedding profiles, non-technical losses, cost of unserved energy and cost of load shedding.
- *Electricity tariff data*: this information concerns the electricity tariffs by type of customer and Province and its expected evolution for the next 10 years, incentives and remuneration schemes for PV and BESS systems and the Annual inflation rate.
- *Additional information*: they refer to any relevant study investigating rooftop PV penetration in South Africa, security and environmental aspects of the country.

3.2. INFORMATION RESPONSE

The following table resume the relevant data provided by the stakeholders that have been used in the study:

Table 2: Data collection description and application

Source	Data/ document	Description and application
NTCSA	*Merged substation and rooftop.shp*	It provides features about both substations and rooftop in the whole South African territory. **Application**: identification of Cape Town municipality borders.
NTCSA	*Status of Embedded Generation in South African Municipalities. pdf*	This report outlines the current state of decentralized energy generation across South African municipalities, highlighting the extent of local renewable energy projects and their integration into the grid. **Application**: analyse the installed solar PV capacity in South Africa per type of customer.
NTCSA	*NTCSA DIGITAL TARIFFS & CHARGES BOOKLET 2024/2025.pdf*	It provides detailed information on the updated electricity tariffs and fees for NTCSA customers, including rate structures and pricing for the upcoming fiscal year. **Application**: electricity price data in the MicroGridsPy simulation.
NTCSA	*COCT Load Shedding All Areas Schedule and Map.pdf*	It details the planned load shedding stages and the affected areas within Cape Town, including a map for tracking power outages and schedules. **Application**: grid availability profile in the MicroGridsPy simulation.
NTCSA	*Cost of Unserved Energy 2022, Annual Update.pdf*	It provides an analysis of the economic losses incurred due to electricity shortages and power outages in 2022. **Application**: cost of unserved energy in the MicroGridsPy simulation
NTCSA	*Estimating the economic cost of load shedding in South Africa.pdf*	This report assesses the financial impact of power outages on the South African economy, including losses in productivity and increased operational costs. **Application**: cost of unserved energy in the MicroGridsPy simulation.
NTCSA	*City of Cape Town Boundary.shp*	It is a digital map that defines the geographic boundaries of the City of Cape Town, used for spatial analysis and mapping applications. **Application**: identification of Cape Town municipality boarders and properly filter the geospatial data in the Technical Potential
COCT	*Rough building footprint.shp*	It is a digital map layer that represents the approximate outlines of buildings within the specified area of Cape Town municipality. **Application**: used as input for PV Technical Potential assessment.
COCT	*City of Cape Town buildings Floor Area2015, 2022 and 2023.xlsx*	It contains data on the floor areas of buildings in Cape Town for the years 2015, 2022, and 2023. **Application**: used for analysing changes in building sizes and urban development over time.

Source	Data/ document	Description and application
COCT	*MUNICIPAL ELECTRICITY MASTER PLAN (MEMP) Electricity pathways for the City of Cape Town by CSIR.pdf*	It outlines strategic pathways for developing a sustainable and reliable electricity system in Cape Town, focusing on future energy needs and supply options. **Application**: assumptions and input data used in the Microgridspy simulations.
COCT	*DEM.tif*	It is the DSM in TIFF format that provides a detailed representation of terrain elevations in Cape Town municipality. **Application**: used, together with building footprint, as input for PV Technical Potential evaluation.
COCT	*Electricity Supply Authority.shp*	It is a shapefile that maps the geographic areas served by different electricity supply authorities, used for visualizing and analysing the distribution of electricity providers. **Application**: filter the geospatial data according to the Supply Authority of COCT
COCT	*Residential Load Curve.xlsx*	This file contains representative Real Power Load curve for Residential customers in the 21/22 Financial Year data. **Application**: load demand profile in the MicroGridsPy simulation.
COCT	*20231016 TOULUMEDV Load Curve 21_22.xlsx*	This file contains representative Real Power Load curve for Time Of Use customers in the 21/22 Financial Year data. **Application**: load demand profile in the MicroGridsPy simulation.
COCT	*SPU Load Curve 21_22.xlsx*	This file contains representative Real Power Load curve for Small Power Users in the 21/22 Financial Year data. **Application**: load demand profile in the MicroGridsPy simulation.
COCT	*Electricity Consumptive tariffs.pdf*	It outlines the rates charged for electricity consumption, detailing various pricing structures based on usage levels, customer categories, and time-of-use. **Application**: electricity price data in the MicroGridsPy simulation.
COCT	*Electricity Generation and Distribution Consumptive.pdf*	It provides information on the costs and tariffs associated with electricity generation and distribution, including consumption rates and the financial aspects of maintaining the supply network. **Application**: electricity price data in the MicroGridsPy simulation.
COCT	*Sales Summaries 21-22, 22-23, 23-24.xlsx*	It includes sales data summaries for the fiscal years 2021-2022, 2022-2023, and 2023-2024, providing insights into sales performance and trends across these periods. **Application**: electricity price data in the MicroGridsPy simulation.

3.3. PUBLIC DATA GATHERED

The following *Table 3* reports a list of the data gathered by CESI from public sources and used as reference in absence of additional data from stakeholders.

Table 3: Data collection from open sources

Source	Data/ document	Description and application
Open Buildings database (W. Sirko, 2021) https://sites.research.google/open-buildings/#download	*Open Buildings (OB) buildings csv file*	A csv file containing the latitude, longitude, area in meters, and geometry of all the buildings in the OB database for the Dominican Republic. **Application**: Calculate the number of buildings and the area of the buildings in the country using QGIS.
ESMAP Global Solar Atlas https://globalsolaratlas.info/download/dominican-republic	*Global Horizontal Irradiation (GHI) raster layer*	The average yearly solar irradiation comprising both the diffuse and direct irradiance on a horizontal plane. Resolution of approximately 250 m x 250 m. **Application**: Calculate the average GHI per building.
ESMAP Global Solar Atlas https://globalsolaratlas.info/download/dominican-republic	*Global Tilted Irradiation (GTI) raster layer*	The average yearly solar irradiation comprising both the diffuse and direct irradiance on a plane inclined at the optimum tilt angle. This is the angle that, at a specific location, maximizes the amount of irradiation received in a year (around 20° for The Dominican Republic). Resolution of approximately 250 x 250 m. **Application**: Calculate the average GTI per building.
Forestry, fisheries and the environment https://egis.environment.gov.za/data_egis/data_download/current	*South African National Land Cover (SANLC) 2020*	The 20 m resolution, raster format South African National Land-Cover 2022 (SANLC 2022) dataset has been generated from automated mapping models (as opposed to conventional image classification procedures), using multi-seasonal 20 m resolution Sentinel 2 satellite imagery. **Application**: Categorize buildings in residential, commercial, industrial, agricultural and informal residential.
PVGIS https://re.jrc.ec.europa.eu/pvg_tools/en/#MR	*Hourly Radiation Data*	The solar radiation data used by PVGIS consists of values for every hour over a period of several years, based on data from satellites and reanalysis. This part of PVGIS makes it possible to download the full set of hourly data for solar radiation and/or PV output power for the chosen location. Unlike the other parts of PVGIS, the data will not be shown as graphs but will be available for download only. **Application**: PV annual Hourly profiles are downloaded for different conditions (optimal slope, average slope etc.) to cover the possible different configurations.
Sun Earth Tools.com https://www.sunearthtools.com/dp/tools/pos_sun.php#annual	*Sun position: altitude and latitude*	Data used to calculate the position of the sun for any location, time, and day. In particular the azimuth and the solar elevation angle are downloaded. **Application**: Sun azimuth and elevation are used as input for the Hillshade function in ArcGIS.
City of Cape Town website https://www.capetown.gov.za/	*City of Cape Town detailed information*	It is the official online platform providing detailed information, services, and updates related to the municipality, including news, public services, local events, and resources for residents and businesses. **Application**: Information on tariffs, incentives, Small-Scale Embedded Generation (SSEG) regulation and solar kits costs.

4. PROOF OF CONCEPT (POC)

This section contains the application of the methodology described in the previous section to the selected study area of Cape Town, using data collected from NTCSA, COCT and public data sources. The Technical Potential analysis allows to compute the maximum capacity of PV installable in the Municipality per each type of customer. This feeds the Economically Viable Potential analysis, that refines the results selecting the optimal sizes of PV and BESS considering economic and reliability aspects. For both steps, both the customer specific results and the aggregated capacity for the whole Municipality are presented.

4.1. TECHNICAL POTENTIAL

The methodology for the PV Technical Potential estimation explained in Section 2 is briefly reported the following diagram

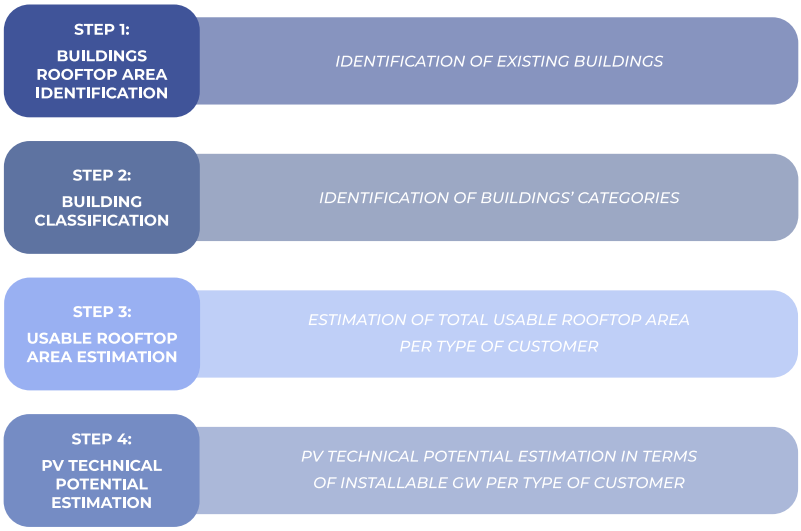


Figure 23: Process for PV Technical Potential estimation

4.1.1. Step 1: Buildings Rooftop Area Identification

To identify the buildings footprints data, the two primary data sources are examined to select the most accurate and suitable option in the Cape Town municipality:

- Open Buildings (OB).
- COCT building data.

Those were clipped with the Municipality boundaries shown in the figure below.



Figure 24: Cape Town municipality boundary

4.1.1.1. Open Buildings (OB)

In this case the existing buildings on the selected site of Cape Town municipality are identified based on the available information and publicly available data from Open Buildings (OB)3. Buildings data for Cape Town municipality are downloaded in the polygon format and added in QGIS (***Figure 25***). In Cape Town area, a confidence score of 0.781 corresponds to a precision of 80%.

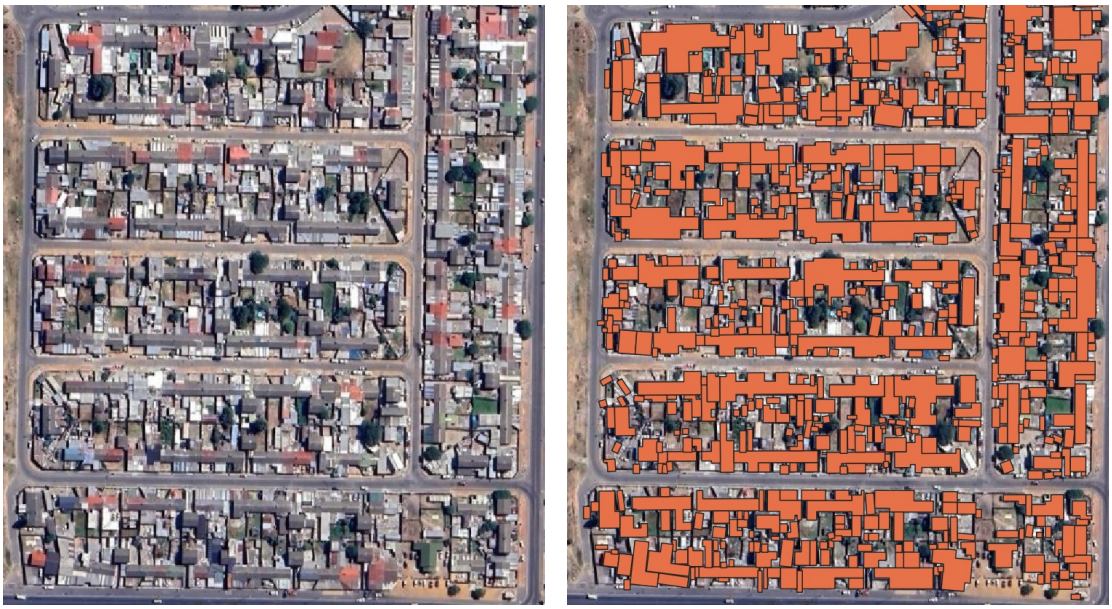


Figure 25: Buildings downloaded from OB

The summary indicators concerning the Cape Town municipality stock based on Open Buildings data are reported. *Table 4* contains some descriptive statistics on the data on the building footprints obtained from OB, which was interrogated based on three separate queries, each applying a different confidence score threshold:

1. Query 1: No filter on the minimum confidence score – includes all data regardless of confidence.
2. Query 2: Confidence score ≥ 0.7 – includes only data with confidence scores at or above 0.7.
3. Query 3: Confidence score ≥ 0.781—includes only data that meets an 80% precision threshold, meaning confidence scores of at least 0.781.

With respect to the first query, the number of buildings in the second query decreases of 16%, while in the third query it decreases of around 50%. However, the total rooftop area decreases of around 5% and 19% respectively, and this indicates that the filter on the footprints with low confidence is limited to the buildings with expected low area. The average building area increases in fact from around 84 m2 of Query 1 to 95.4 m2 and then to 133.1 m2 to Query 2 and 3, respectively.

Table 4: Statistical indicators on OB buildings layer

	No filter	Confidence score ≥ 0.7	Confidence score ≥ 0.781
N° of buildings	2,102,064	1,764,837	1,078,814
Total surface	176,798,289.6 (176,798 km^2)	168,424,088.9 (168,424 km^2)	143,595,219.7 (143,595 km^2)
Mean value	84.10	95.43	133.1
Standard deviation	262.5	284.7	356.4
Min	2.5	2.5	2.5
Q1 *(first quartile, containing 25% of the sample data)*	20.6	24.9	43.1
Median *(second quartile, containing 50% of the sample data)*	40.6	48.8	77.3
Q3 *(third quartile, containing 75% of the sample data)*	88.7	103.5	148.1
Max	46,701.7	46,701.7	46,701.7

4.1.1.2. COCT building data

The second approach to identify the buildings on the Cape Town territory is to use information and data given from the City of Cape Town (COCT). Buildings footprint data for Cape Town municipality in the form of a multi-polygon shapefile layer are added in QGIS.



Figure 26: COCT building footprint

The summary descriptive statistics concerning the Cape Town municipality stock based on COCT data are reported in ***Table 5***.

Table 5: Statistical indicators on COCT building footprint layer

Indicator	Value
N° of buildings	847,963
Total surface	164,997,966.6 (164,997 km2)
Mean value	194.6
Standard deviation	762.8
Min	0.99
Q1 *(first quartile, containing 25% of the sample data)*	22.3
Median *(second quartile, containing 50% of the sample data)*	69
Q3 *(third quartile, containing 75% of the sample data)*	211.4
Max	172,367.4

The next *Table 6*, shows a comparison of the COCT layer with the most similar case in the Open Buildings (OBs) dataset, particularly the one with a confidence level of 0.7 (Query 2). The total rooftop surface is well aligned in the two databases while the single building surface is significantly higher in COCT. In the OB dataset, buildings are represented as numerous small rectangles, which do not always accurately reflect the total real rooftop area of the single building. On the other hand, the COCT layer uses larger rectangles, sometimes combining more than one actual building. The actual average building surface probably would lie in the middle between the values from the two databases. However, for the purpose of calculating Technical Potential, it is not essential to precisely capture the shape of each individual building. Instead, the goal is to identify the total rooftop surface area available for potential PV installation.

Table 6: Total and specific average surface comparison between OB and COCT

	OB (confidence level 0.7)	COCT
Total surface	168,424 km^2	164,997 km^2
Mean building surface	95.43 m^2	194.6 m^2

The COCT layer was chosen as the most suitable for further analysis due to its superior alignment with both the Google satellite imagery and the area's Digital Surface Model. This precision and relevance make it a solid foundation for the next phases of analysis.

4.1.2 Step 2: Buildings Classification

This section reports the results of the process of the classification of the buildings based on the available information from NTCSA, COCT and available data. Buildings are classified in five categories:

1. Residential.
2. Informal Residential.
3. Industrial.
4. Commercial.
5. Agricultural.

According to the methodology described in Chapter 2, the classification process involves associating each building with further attributes from two input layers:

1. South African National Land Cover (SANLC). The 73 categories of the SANLC, shown in detail in Annex B, are reclassified as follows:

Table 7: SANLC category reclassification

SANLC categories	SANLC categories reclassified
From 32 to 46, from 57 to 60 and 73	Agricultural
From 47 to 50 and 55-56	Residential
From 51 to 54	Informal residential
65	Commercial
66 and from 68 to 72	Industrial
**Categories from 1 to 31, from 61 to 64 and 67 are not relevant for the scope of the analysis.*	

2. Census 2011, EA-Type. For the City of Cape Town, the Census contains nine categories grouped into the five that are relevant for the scope of the analysis:

Table 8: Census 2011, EA-type category reclassification

Census 2011 EA-TYPE categories	Census 2011 EA-TYPE categories reclassified
Collective living quarters	Residential
Formal residential	
Parks and recreation	
Informal residential	Informal Residential
Vacant	
Industrial	Industrial
Commercial	Commercial
Small holdings	Agricultural
Farms	

In QGIS/ArcGIS software, by means of the Zonal Statistics tool, to each building is associated the SANLC and Census reclassified categories. Priority, as explained in the methodology, is given to the SANLC, and the Census type is used only in areas were the categorization from SANLC is not enough to determine the buildings final use.

Results for a portion of the municipality are reported in ***Figure 27***.



Figure 27: Buildings classification

Table 9 shows the Total Rooftop Area for each building category.

Table 9: Total building area per category

Category	Total Rooftop Area [km²]
Residential	112.7
Informal Residential	23.95
Commercial	18.28
Industrial	4.99
Agricultural	4.92
Total	**164.9**

As visible in ***Figure 28***, almost 68% of the Total Rooftop Area is characterized as Residential, followed by Informal Residential (16%), Commercial (10%), Industrial (3.1%), and Agricultural (2.7%).

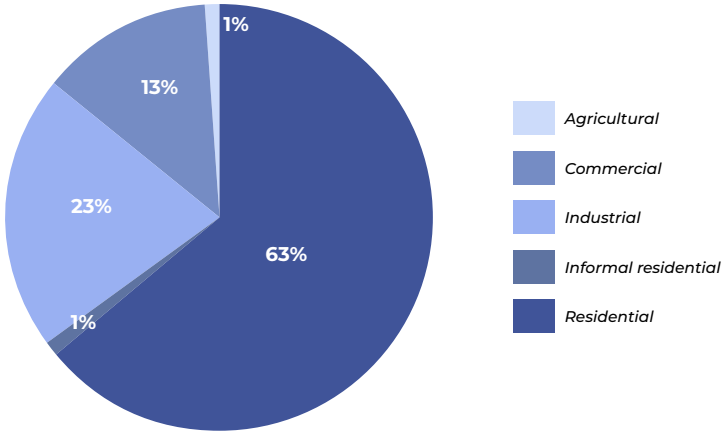


Figure 28: Cape Town building classification-total rooftop area percentages

Informal settlements refer to housing areas that are built without official planning or government authorization. These settlements are often characterized by inadequate infrastructure, lack of basic services (such as water, electricity, and sanitation), and homes constructed with temporary or makeshift materials. As agreed with NTCSA, informal residential are removed from the suitable areas for rooftop PV installations, due to technical limits (rooftop may not be suited to sustain the weight of PV modules), and economic reasons (without dedicated incentives, residents may not be able to face the cost of PV installations).

For what concerns agricultural structures, since they are less than 1% of the total, they have been grouped together with commercial buildings.

Figure 29 and *Table 10* report the new and final categorization with the associated total building area.

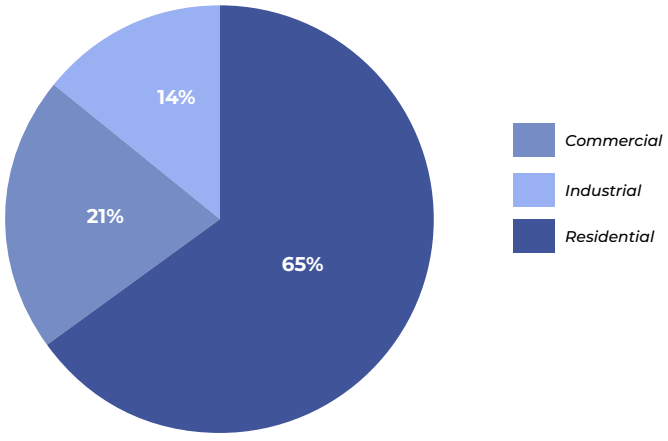


Figure 29: Updated Cape Town buildings' categorization

Table 10: Total building area per category reclassified

Category	Total Rooftop Area [km²]
Residential	112.8
Commercial/Agricultural	23.2
Industrial	4.99
Total	**140.9**

4.1.3. Step 3: Usable Rooftop Area Estimation

The availability of a Digital Surface Model (DSM) for the Cape Town municipality received by the COCT enables the application of the full methodology explained in Section 2.1.3, to accurately define the shadowing, inclination and orientation of rooftop planes. This process involves several steps: after defining the shading, slope and orientation, pixels (1x1 m) are filtered according to the methodology. This involves excluding areas that are not suitable for solar panel installation due to factors such as excessive shading or unfavourable roof angles.

Using the DSM, the ArcGIS **Hillshade function** generates shadow maps of the rooftops. To accurately simulate solar radiation, sun azimuth and altitude data are downloaded[13] in Cape Town municipality for four representative days of the year 2023: January 1st, April 1st, July 1st, and October 1st. These dates are selected to cover different seasons and capture variations in solar exposure throughout the year. For instance, on January 1st, the simulation will assess the solar exposure from 7 a.m. to 7 p.m., with calculations performed every two hours (*Table 11*). Results for four hours of the day for January 1st are reported in *Figure 30*.

Table 5: Statistical indicators on COCT building footprint layer

Date:	1/1/2023	
Coordinates:	-33.928992, 18.417396	
Hour	Elevation	Azimuth
7:00:00	14.67	108.15
9:00:00	39.04	93.53
11:00:00	63.67	72.76
13:00:00	78.86	347.6
15:00:00	59.52	282.36
17:00:00	34.75	263.88
19:00:00	10.61	249.32

[13] *https://www.sunearthtools.com/*

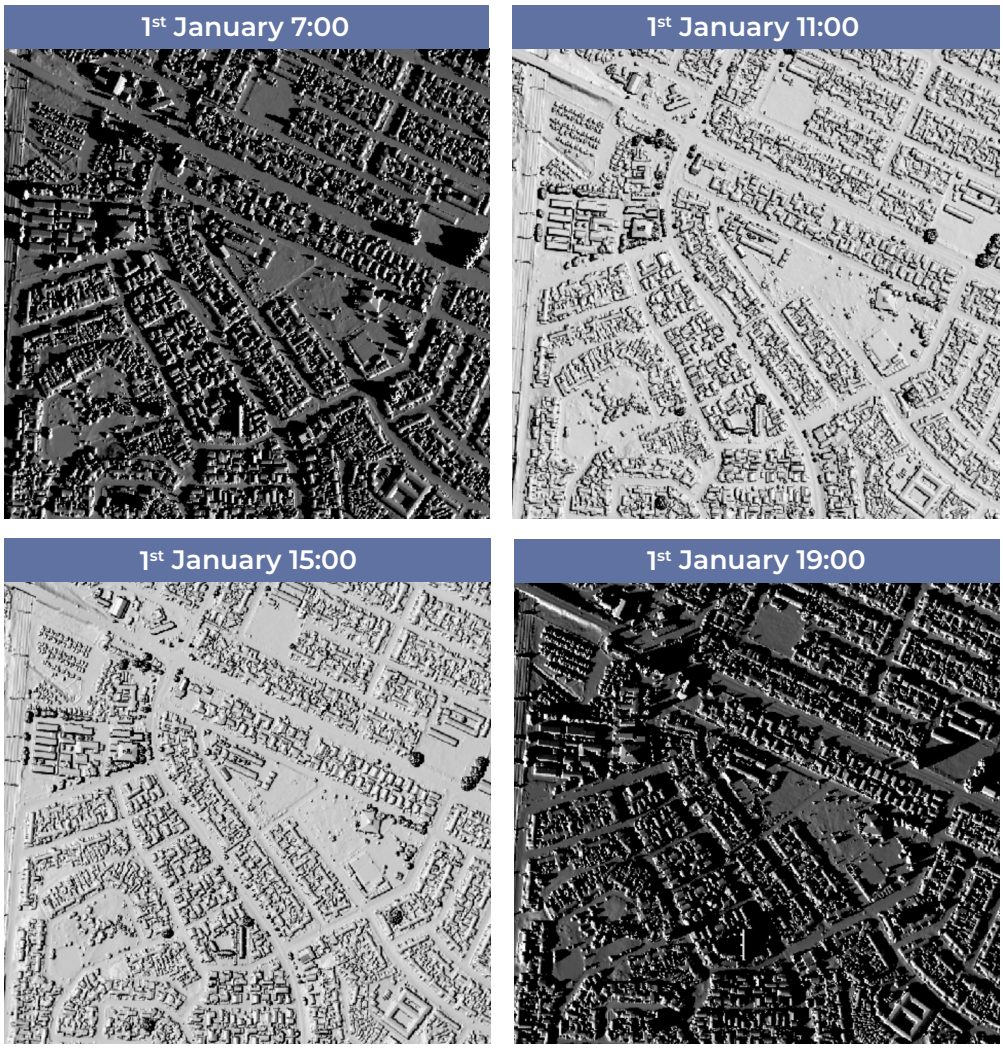


Figure 30: Hillshade function output

Overall, from the four selected representative days, 24 layers are downloaded and processed as follows:

- *Binary Conversion*: each of the 24 layers is first transformed into binary format. In this transformation, value 0 represents pixels that are shaded, indicating periods when the rooftop is not exposed to direct sunlight; value 1 represents all other pixels that are illuminated, indicating periods of solar exposure.
- *Layer aggregation*: after converting each layer to binary format, these layers are summed to create a single aggregated layer. This aggregated layer has as minimum value 0, representing areas that were never illuminated during any of the simulated times; maximum value of 24, indicating pixels that were illuminated for all the 24-time intervals.
- *Value filtering*: the aggregated layer is then filtered to retain only those pixels with values greater than 12. This threshold is set to ensure that pixels must be exposed to sunlight for at least 50% of the time across the 24 intervals. By selecting only those pixels, the analysis focuses on areas that receive substantial sunlight, ensuring a more accurate assessment of rooftop suitability for solar panel installation.
- *Results*: after filtering, approximately 9.1% of the total rooftop area was found unsuitable due to shading. The remaining area meets the sunlight exposure criteria, providing a more accurate assessment of viable rooftop space for solar panel installation.

Secondly, the ArcGIS **Slope function** is utilized to generate a corresponding Slope layer, which provides information on the slope of each pixel representing the rooftops of buildings. Rooftops are classified as flat if their slope is less than 10 degrees. Rooftops with a slope between 10 degrees and 60 degrees are classified as tilted. Pixels with slope values greater than 60 degrees are excluded from the analysis, in accordance with the established methodology. These extreme slopes are considered unsuitable for solar panel installation and do not contribute to the assessment of rooftop solar potential. The results of the analysis, disaggregated by customer type (such as residential, commercial, or industrial), are presented in *Table 12*.

Table 12: Average Slope results by customer type

Average Slope	Residential	Commercial	Industrial
Slope (degrees)	26.09	22.84	17.57
Slope (radians)	0.4553	0.3986	0.3066

Results: The area removed due to excessive steepness is around 8% of the Total Rooftop Area.

To determine the orientation of rooftops, the ArcGIS **Aspect tool** is employed. This tool calculates the direction that each rooftop surface faces, providing information for assessing solar exposure potential. For tilted rooftops, orientations ranging from south-east to south-west are excluded from the analysis. This is done because these directions generally receive less sunlight, making them less suitable for effective solar energy capture. For flat rooftops, all directions are considered acceptable, since they can capture sunlight from any direction during the day. The outcomes of these calculations are summarized in *Table 13*.

Table 13: Rooftop type by customer type

Rooftop type	Residential	Commercial	Industrial
Flat	0.6%	12.6%	17.2%
Tilted	99.4%	87.4%	82.8%

Results: Due to unfavourable orientation, around 26% of the roofs is removed from the analysis.

The average Suitable Rooftop Area coefficients for both flat and tilted rooftops, denoted as $coef\ f_{suit,flat}$ and tilted $coef\ f_{suit,tilt'}$ respectively, account for reductions due to shading, slope, and orientation, and are listed in *Table 14*. These coefficients represent the percentage of the total rooftop area deemed suitable for solar installation.

Table 14: Average suitable area coefficients by customer type

Orientation	Residential	Commercial	Industrial
Flat	72%	78%	80%
Tilted	63%	58%	58%

The total Usable Rooftop Area is then calculated by applying usability coefficients, as outlined in the methodology: 70% for flat rooftops ($coeff_{usab,flat}$) and 73% for tilted rooftops ($coeff_{usab,tilt}$) a The results, broken down by customer type and roof type, are detailed in ***Table 15***.

Table 15: Total area, suitable area and usable area results by customer type

Category	Total area [km²]		Suitable area [km²]		Usable area [km²]	
	Flat	Tilted	Flat	Tilted	Flat	Tilted
Residential	0.6	103.0	0.45	64.6	0.3	52.7
Commercial	4.3	30.0	3.5	18.1	2.4	14.4
Industrial	3.8	18.4	3.2	12.2	2.2	9.4
Total	**8.7**	**151.4**	**7.1**	**94.9**	**4.9**	**76.5**

4.1.4. Step 4: PV Technical Potential Estimation

In South Africa, Jinko Solar modules are among the most widely used solar PV panels. For these reasons, they are selected as reference for initiating the calculation of the PV Technical Potential. Based on technical data sheets, the total PV capacity is calculated by performing the following calculations (As per Methodology in section 2.1.4):

i. *Select Candidate PV model*: The JinkoSolar JKM410M-72H-V panel[14], with a peak output of 410 W and dimensions of 2065 mm x 996 mm (2.06 m²), allows for the calculation of the occupation factor (m²/kW). This factor, representing the area required per kilowatt of power, is derived by dividing the panel's area by its power rating, resulting in an occupation factor of 5.02 m²/kW.
ii. *Calculate total PV Capacity [kW]*: For each building, the PV Capacity (in kW) is calculated by dividing the building's Usable Rooftop Area by the 5.02 m²/kW occupation factor derived in step (i). The total PV capacity for Cape Town is then obtained by summing the PV capacities calculated for each building across all identified buildings in the study area.
iii. *Assign Maximum PV Capacity per User*: ***Table 16*** presents cumulative data for the total Usable Rooftop Area and the total PV capacity (in gigawatts) segmented by customer type. The power density is determined by taking the ratio of the total rooftop area to the total possible PV capacity.

[14] *The module was selected among the ones most installed in South Africa, as shared by NTCSA and referenced in ANNEX C.*

Table 16: Total Usable Rooftop Area and total PV capacity

Category	Total area [km²]	Usable Area [km²]	Total PV capacity [GW]			Power density
			Tilted + Flat	Flat	Tilted	m²/kW
Residential	103.6	53.0	10.6	0.06	10.5	9.8
Commercial	34.3	16.9	3.4	0.48	2.9	10.1
Industrial	22.3	11.6	2.3	0.45	1.9	9.6
Total	**160.2**	**81.5**	**16.3**	**0.99**	**15.3**	**9.8**

The same process is then performed to obtain results only for buildings served by COCT, excluding the areas supplied by NTCSA in the Cape Town Municipality. ***Figure 31*** reports the share of buildings supplied by the two different electricity supply authorities. As visible, 77% of buildings Total Rooftop Area is within areas supplied by COCT while the remaining is served by NTCSA.

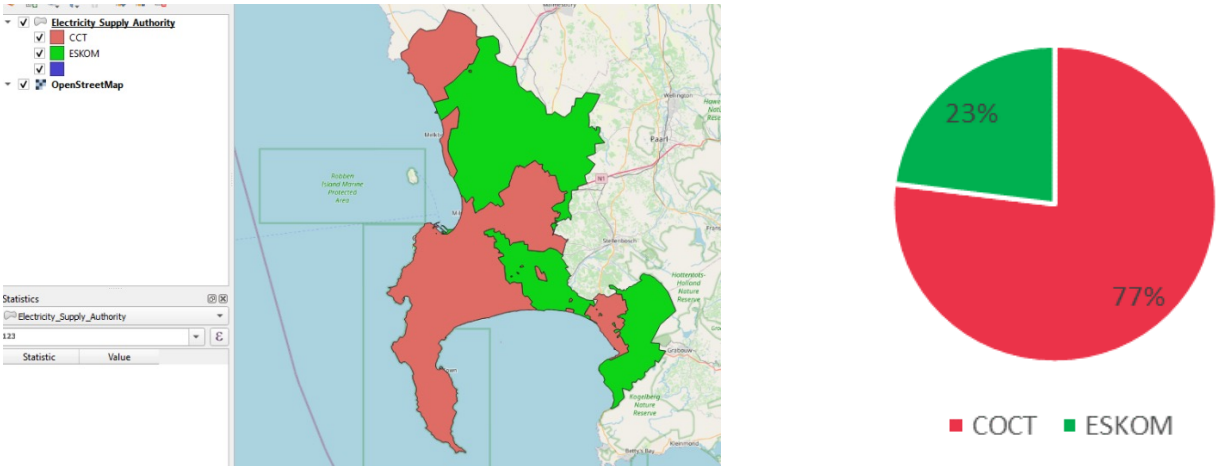


Figure 31: Electricity Supply Authority

Results for total Rooftop Area, Usable Roofotp Area, PV capacity and power density referred to COCT supply authority are reported in ***Table 17***.

Table 17: Total Usable Rooftop Area and total PV capacity supplied by COCT

Category	Total area [km²]		Usable Area [km²]		PV capacity (GW)		Power density
	Flat	Tilted	Flat	Tilted	Flat	Tilted	m²/kW
Residential	0.4	79.3	0.2	40.4	0.04	8.0	9.8
Commercial	3.5	24.4	1.9	11.6	0.40	2.3	10.3
Industrial	2.5	13.2	1.5	6.8	0.29	1.4	9.5
Total	**6.4**	**116.9**	**3.6**	**58.8**	**0.73**	**11.7**	**9.9**

At this stage of the analysis, an additional categorization is applied to residential customers supplied by COCT based on their income levels, which are determined by the electricity tariff they are charged. Data on the number of customers per tariff are retrieved from the "*Electricity Consumptive Tariffs_23_24*" provided by COCT. Residential customers are classified into high income, middle income, and low-income categories. More than 300'000 customers are categorized as high income, as they are subject to the Home User tariff. Similarly, approximately 308'000 customers fall into the middle-income group, as they are charged the Domestic tariff, while around 160'000 customers are classified as low income, paying according to the Lifeline tariff.

To disaggregate the total residential rooftop area into the high-, middle- and low-income classes the following assumption, based on a validation on a subset of suburbs is made: middle income and high-income customers have a usable rooftop area that is respectively the double and 3 times the one of low income customers.

The results for the total and usable rooftop area per customer, along with the maximum PV capacity for each user, are presented in *Table 18*.

Table 15: Total area, suitable area and usable area results by customer type

Customer	N customers [#]	Total rooftop area [m²]	Usable rooftop area [m²]	Max PV capacity [kW]
Residential high income	308,589	176	90	18
Residential middle income	135,726	117	60	12
Residential low income	162,079	59	30	6
Commercial	**28,941**	**968**	**470**	**94**
Industrial	**1,406**	**11,204**	**5,887**	**1,177**

4.2. ECONOMICALLY VIABLE POTENTIAL

The methodology for the PV Economically Viable Potential estimation is reported below. The work presented is a proof of concept and, as such, it does not have the goal to simulate all the possible combinations of the simulation parameters and customer behaviours, but rather a set of selected options to obtain some broader insights on the PV potential in South Africa.

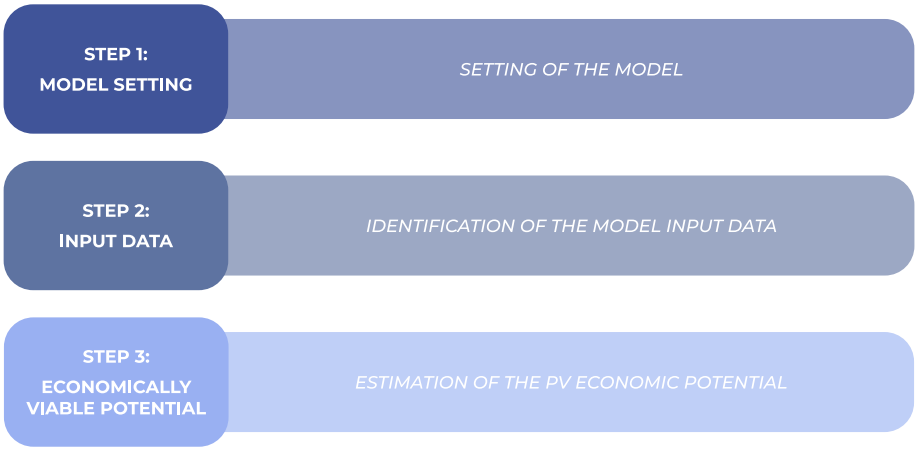


Figure 32: Process for PV Economically Viable Potential evaluation

4.2.1. Step 1: Model Setting

In accordance with NTCSA and the interviewed stakeholders and following the categories found during the data collection phase and the calculation of the Technical Potential, five different **archetypes of customers** were selected and modelled in the simulation:

- Residential – low income.
- Residential – middle income.
- Residential – high income.
- Commercial.
- Industrial.

To each of these categories is associated a different load demand curve, rooftop space availability (as from the Technical Potential results), electricity tariff and costs for the PV and BESS components. The combination of the PV and BESS capacity that these types of customers may be willing to install represents, with a good degree of approximation, the expected new installations in the COCT.

In South Africa, one of the major drivers for PV and BESS installations is the risk of **load shedding**, which stimulates customers to invest in backup sources to increase the grid reliability. Two scenarios are hence tested with the model, to assess which could be the different customers behaviour in the presence or not of load shedding. In the report, these will be called as follows:

- *Load shedding* – the grid electricity is not available in certain hours, according to the historical load shedding profiles.
- *Perfect grid* (i.e., no load shedding) – the grid is always available; this will hopefully be the trend of the country in the next years.

Another important driver for the installations is the economic convenience of the solution, which, among others, also depends on the possibility to be remunerated for the surplus electricity produced and injected onto the grid. Two scenarios are tested:

- *Purchase/sell electricity* – electricity can be purchased and sold from/to the grid.
- *Purchase only electricity* – electricity can be purchased only and any possible PV surplus injected onto the grid will not be remunerated.

Lastly, the maximum **Depth of Discharge (DoD)**[15] of the battery is considered, to simulate two different behaviours of the customers willing to either use the storage system at full potential or just as a backup system for security reasons. The cases are respectively:

- *Maximum DoD 80%* – the battery storage capacity is utilized nearly to its maximum potential, with a minimum SOC of 20% given by BESS technical limits. This is the cost-effective way of using BESS and hence used as the base scenario for all the users.
- *Maximum DoD 20%* – the battery storage capacity is used only at the 20% of its entire potential, with a minimum SOC of 80%. This scenario, suggested by NTCSA, represents users who are highly concerned about the risk of power outages. To reduce their loss of load probability (the likelihood of experiencing a power shortage), these users maintain their batteries close to full capacity at all times. This behaviour minimizes the chance of being without electricity. This scenario is a borderline case applied as a sensitivity case only to High Income Residential users.

All the scenarios considered in the simulations are summarized in the table below. Combining these scenarios, it results a total of 24 simulations.

Table 19: Simulation cases list

Simulation item	Simulation cases
Customer	Residential low income
	Residential middle income
	Residential high income
	Commercial
	Industrial
Load shedding	Load shedding
	Perfect grid
Incentives	Purchase/sell electricity
	Purchase only electricity
DoD	Maximum DoD 80%
	Maximum DoD 20% (only for high income residential users)

[15] *It describes the percentage of a battery's total capacity that has been used or discharged. It represents the complementary of the State of Charge (SoC). In formula: SoC=1-DoD. If a battery is fully charged, the DoD is 0%, and if it's completely discharged, the DoD is 100%.*

4.2.2. Step 2: Input Data Definition

The necessary input data are detailed in this Section, in particular:

- Usable rooftop area.
- Grid availability.
- Load demand.
- Electricity Tariffs.
- PV profiles.
- PV and battery costs.
- Other parameters.

4.2.2.1. Usable rooftop area

The usable rooftop area per customer was computed in the Technical Potential evaluation and reported in *Table 18*. This is provided in input to *Microgridspy* together with the modules power density of 5.02 m²/kW, for determining the maximum capacity installable. Those technical limits are larger than the SSEG size limitations provided in the Requirements for Small-Scale Embedded Generators (COCT, 2023). To make the analysis more general, however, the regulatory size limits are not included, and the tool is free to optimize the system up to the maximum technical size.

4.2.2.2. Grid availability

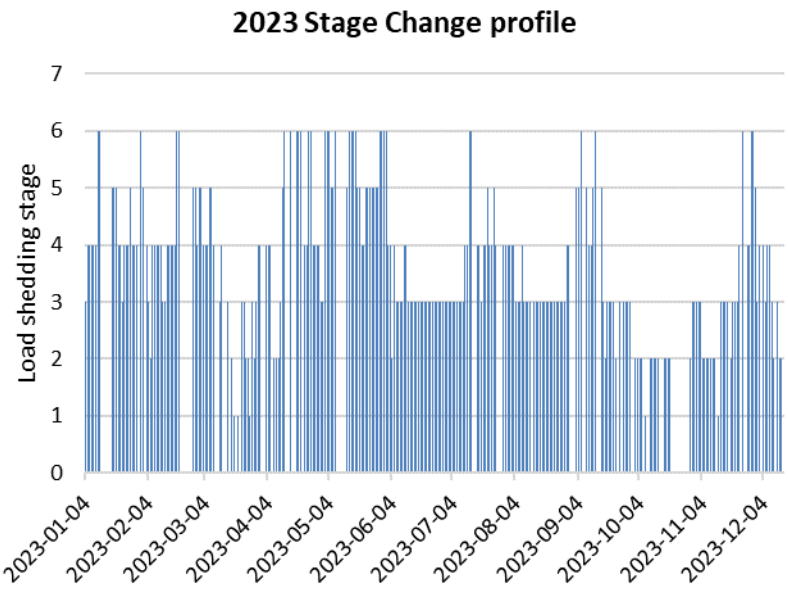
The historical load shedding data in the Cape Town Municipality were provided by NTCSA. Those data were processed and used to create an hourly grid availability profile experienced by the single users, as requested in input by the *MicroGridsPy* model:

- 1 when the grid is available, and electricity can normally flow.
- 0 when there is load shedding, meaning that the grid electricity is not available.

NTCSA provided both the yearly COCT load shedding stages, experienced in the Cape Town areas supplied by the COCT, which has higher reliability levels thanks to the installed hydro pumping plants, and the NTCSA load shedding stages, experienced in the Cape Town areas supplied by NTCSA. The latter was selected for the simulations, to have more conservative and generalizable results. The selected year for the simulation is the 2023 given the worst load shedding conditions, but data date back to 2014 and the processed files could be used by NTCSA for further analyses.

The raw load shedding files contain a time profile holding the changes in the load shedding stage in Cape Town from 2014 to 2024, of which some example values are shown in the table below. Notice that the datetime column contains only the hours when a stage change has occurred.

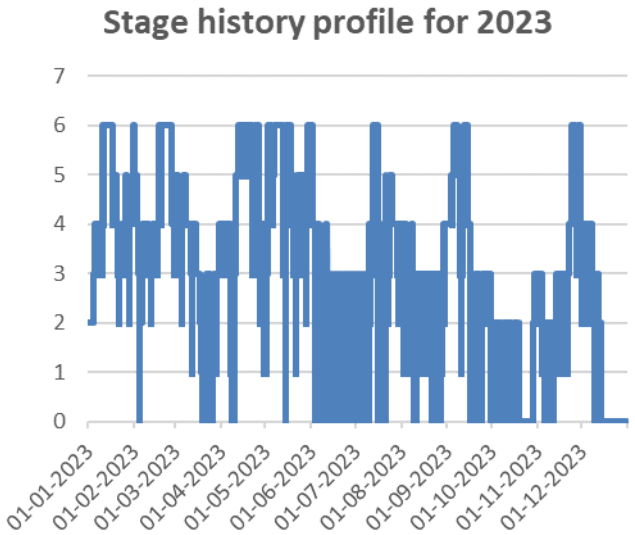
Table 20: Raw load shedding historical data

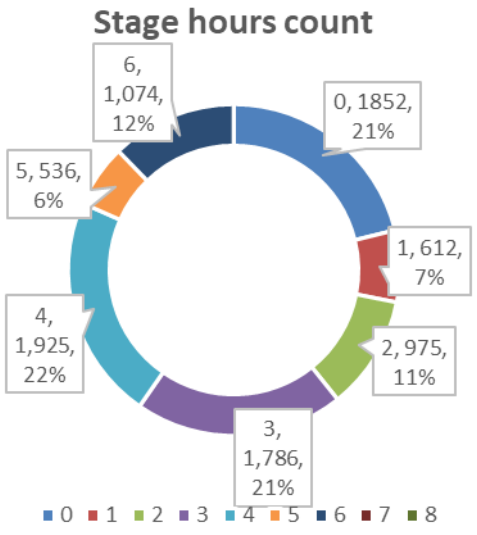


DateTime	Stage
2023-12-14 5:00:00	0
2023-12-13 16:00:00	2
2023-12-13 0:00:00	0
2023-12-12 16:00:00	2
2023-12-12 12:00:00	0
2023-12-12 7:00:00	2
2023-12-11 5:00:00	3
2023-12-09 21:00:00	0
...	...

The above data were expanded to obtain the complete 8760 hourly profile (***Table 21***), called stage history, which represents the hourly profile of the historical defined stage. The number of hours in which the system experienced the different load shedding stages is reported in the pie chart below. The Cape Town Municipality experiences uninterrupted electricity supply for only 21% of the total hours, meaning that during this limited time, no areas are subjected to power curtailment. During the rest of the time, one or more areas are curtailed according to the severity of the load shedding stage and the rotating load shedding schemes as explained later.

Table 21: Hourly load shedding profile and stage hours count





For the sake of the study, it is necessary to recreate the load shedding hourly profiles experienced by single users according to the rotating load shedding schemes. Those are implemented on the 16 zones of Cape Town in such a way that the higher the load shedding severity, the more are the zones experiencing load shedding at the same time. Thanks to the rotation, over the month, zones experience the same hours of load shedding. *Table 22* shows the stage *schedule* of the first two hours of the day: as an example, the first day of the month zone 1 experiences load shedding if the stage is greater or equal than 1, zone 5 if the stage is equal or greater than 2, and so on.

Given the described data a load shedding profile for 2023 was obtained. Load shedding is existing (*Load shedding=1*) only when the stage schedule is lower than the historical stage profile and when none of them is zero:

$$Load\ shedding(t) = \begin{cases} 1, & if \quad Stage\ schedule(t) \leq Stage\ history(t) \\ 0, & if \quad Stage\ schedule(t) > Stage\ history(t) \\ 0, & if \quad Stage\ schedule(t) = 0 \\ 0, & if \quad Stage\ history(t) = 0 \end{cases}$$

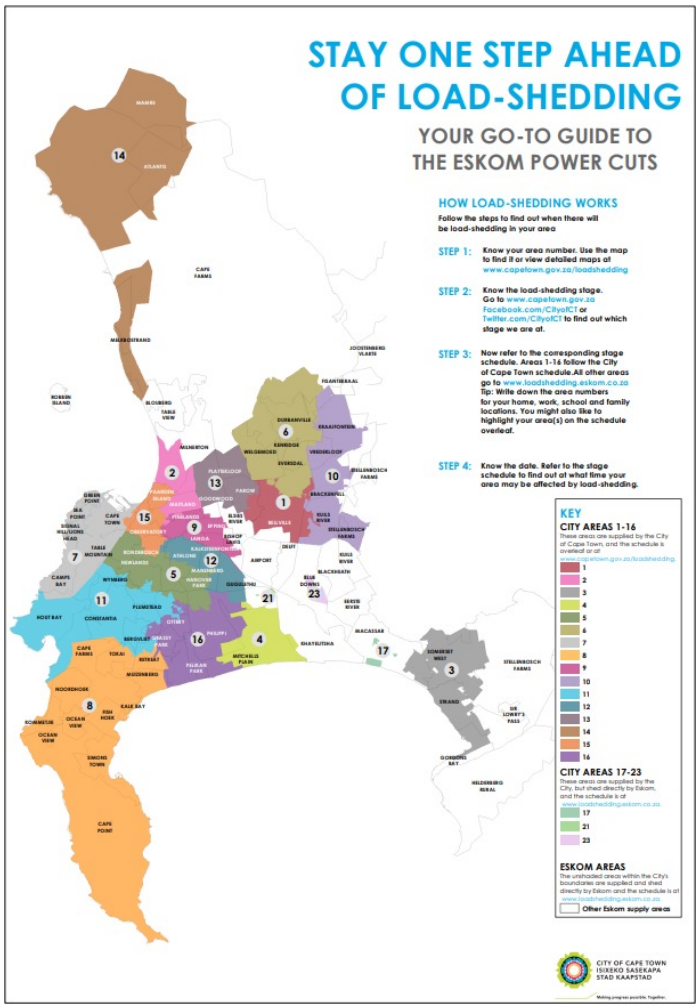


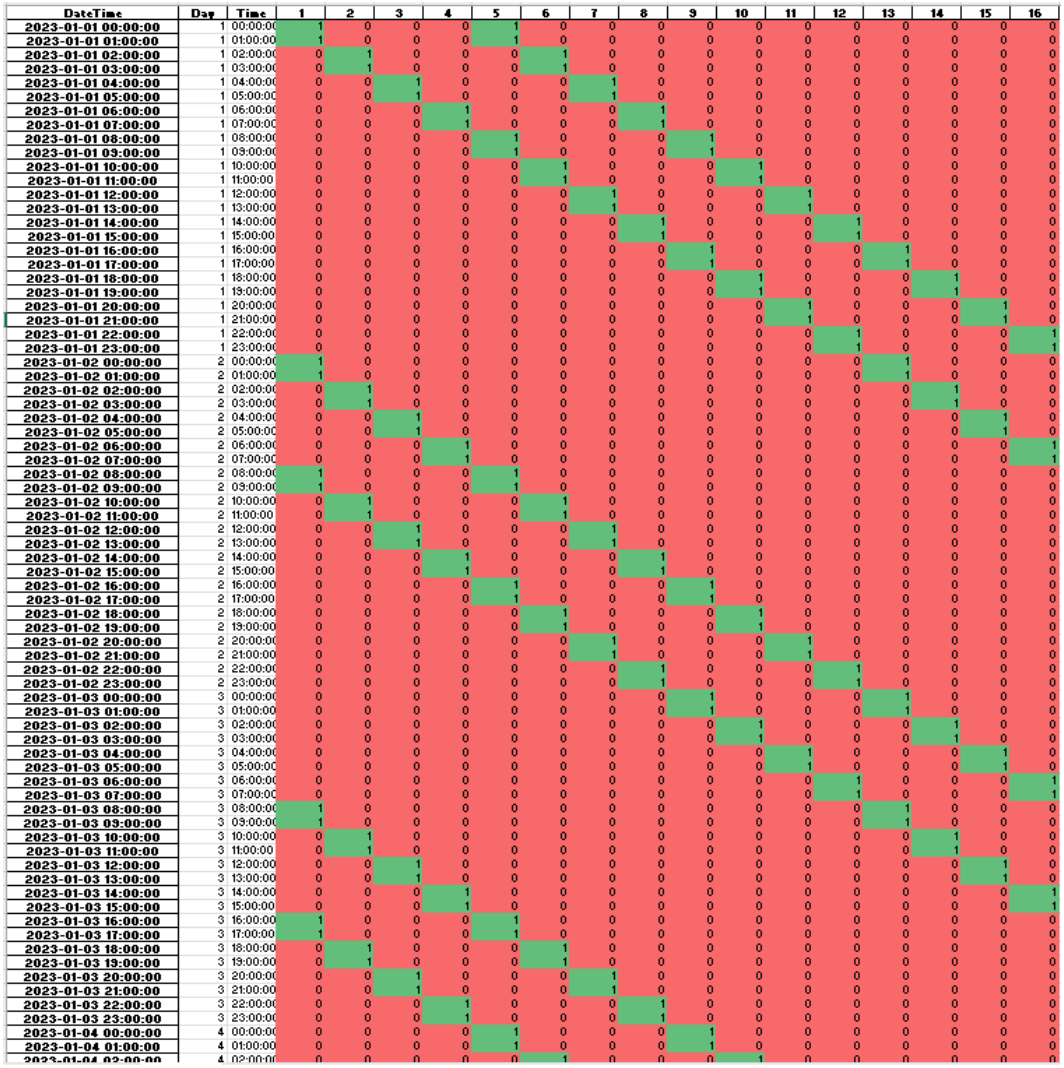
Figure 33: Cape Town Supply Areas

Table 22: Load shedding calendar in CapeTown – first two hours

Hour	Stage	Day of the month																												
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
00:00 – 02:00	1	1	13	9	5	2	14	10	6	3	15	11	7	4	16	12	8	5	1	13	9	6	2	14	10	7	3	15	11	8	4	16
	2	5	1	13	9	6	2	14	10	7	3	15	11	8	4	16	12	9	5	1	13	10	6	2	14	11	7	3	15	12	8	4
	3	9	5	1	13	10	6	2	14	11	7	3	15	12	8	4	16	13	9	5	1	14	10	6	2	15	11	7	3	16	12	8
	4	13	9	5	1	14	10	6	2	15	11	7	3	16	12	8	4	1	13	9	5	2	14	10	6	3	15	11	7	4	16	12
	5	11	12	8	4	16	13	9	5	1	14	10	6	2	15	11	7	3	16	12	8	4	1	13	9	5	2	14	10	6	3	15
	6	15	16	12	8	4	1	13	9	5	2	14	10	6	3	15	11	7	4	16	12	8	5	1	13	9	6	2	14	10	7	3
	7	3	4	16	12	8	5	1	13	9	6	2	14	10	7	3	15	11	8	4	16	12	9	5	1	13	10	6	2	14	11	7
	8	7	8	4	16	12	9	5	1	13	10	6	2	14	11	7	3	15	12	8	4	16	13	9	5	1	14	10	6	2	15	11

The grid availability profile – used as input in the model – is obtained as a simple complementary profile of load shedding, i.e. 1 when there is no load shedding and 0 when there is.

The resulting load shedding profile for 2023 (***Figure 34***) shows that load shedding occurs for the 17.73% of the time in all the Zones, corresponding to an overall grid availability equal to 82.27%. To run the simulations, zone 1 was selected since all zones are equivalent being each one's schedule profile a translated version of all the others.



DateTime	Day	Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
2023-01-01 00:00:00	1	00:00:00	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2023-01-01 01:00:00	1	01:00:00	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2023-01-01 02:00:00	1	02:00:00	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2023-01-01 03:00:00	1	03:00:00	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2023-01-01 04:00:00	1	04:00:00	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2023-01-01 05:00:00	1	05:00:00	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2023-01-01 06:00:00	1	06:00:00	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
2023-01-01 07:00:00	1	07:00:00	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
2023-01-01 08:00:00	1	08:00:00	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
2023-01-01 09:00:00	1	09:00:00	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
2023-01-01 10:00:00	1	10:00:00	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
2023-01-01 11:00:00	1	11:00:00	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
2023-01-01 12:00:00	1	12:00:00	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
2023-01-01 13:00:00	1	13:00:00	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
2023-01-01 14:00:00	1	14:00:00	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
2023-01-01 15:00:00	1	15:00:00	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
2023-01-01 16:00:00	1	16:00:00	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
2023-01-01 17:00:00	1	17:00:00	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
2023-01-01 18:00:00	1	18:00:00	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
2023-01-01 19:00:00	1	19:00:00	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
2023-01-01 20:00:00	1	20:00:00	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
2023-01-01 21:00:00	1	21:00:00	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
2023-01-01 22:00:00	1	22:00:00	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
2023-01-01 23:00:00	1	23:00:00	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
2023-01-02 00:00:00	2	00:00:00	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2023-01-02 01:00:00	2	01:00:00	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2023-01-02 02:00:00	2	02:00:00	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
2023-01-02 03:00:00	2	03:00:00	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
2023-01-02 04:00:00	2	04:00:00	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
2023-01-02 05:00:00	2	05:00:00	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
2023-01-02 06:00:00	2	06:00:00	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
2023-01-02 07:00:00	2	07:00:00	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
2023-01-02 08:00:00	2	08:00:00	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2023-01-02 09:00:00	2	09:00:00	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2023-01-02 10:00:00	2	10:00:00	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2023-01-02 11:00:00	2	11:00:00	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2023-01-02 12:00:00	2	12:00:00	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2023-01-02 13:00:00	2	13:00:00	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2023-01-02 14:00:00	2	14:00:00	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
2023-01-02 15:00:00	2	15:00:00	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
2023-01-02 16:00:00	2	16:00:00	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
2023-01-02 17:00:00	2	17:00:00	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
2023-01-02 18:00:00	2	18:00:00	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
2023-01-02 19:00:00	2	19:00:00	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
2023-01-02 20:00:00	2	20:00:00	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
2023-01-02 21:00:00	2	21:00:00	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
2023-01-02 22:00:00	2	22:00:00	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
2023-01-02 23:00:00	2	23:00:00	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
2023-01-03 00:00:00	3	00:00:00	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
2023-01-03 01:00:00	3	01:00:00	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
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2023-01-03 07:00:00	3	07:00:00	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
2023-01-03 08:00:00	3	08:00:00	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2023-01-03 09:00:00	3	09:00:00	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2023-01-03 10:00:00	3	10:00:00	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
2023-01-03 11:00:00	3	11:00:00	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
2023-01-03 12:00:00	3	12:00:00	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
2023-01-03 13:00:00	3	13:00:00	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
2023-01-03 14:00:00	3	14:00:00	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
2023-01-03 15:00:00	3	15:00:00	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
2023-01-03 16:00:00	3	16:00:00	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2023-01-03 17:00:00	3	17:00:00	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2023-01-03 18:00:00	3	18:00:00	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2023-01-03 19:00:00	3	19:00:00	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2023-01-03 20:00:00	3	20:00:00	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2023-01-03 21:00:00	3	21:00:00	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2023-01-03 22:00:00	3	22:00:00	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
2023-01-03 23:00:00	3	23:00:00	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
2023-01-04 00:00:00	4	00:00:00	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
2023-01-04 01:00:00	4	01:00:00	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
2023-01-04 02:00:00	4	02:00:00	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0

Figure 34: Load shedding profile in the 16 Cape Town zones

For generating the hourly load demand profile for each user category, the information on the historical monthly energy demand in the COCT together with a sample of synthetic demand profiles provided by COTC and feedback from NTCSA were used.

We proceeded as follows:

1. The synthetic profiles received from the COCT were rescaled to align with the average monthly energy consumption as per the COCT 2023-2024 sales summaries, associating to each customer a reference tariff as per Table 23.
2. The profiles were then further readapted to reflect realistic peak load values[16], according to NTCSA feedback, and considering the diversity factors typically used in distribution systems[17], as a metrics to convert the synthetic load profiles into load curves that can be considered representative of the behavior of a single-user.

Table 23: Annual energy and peak load by customer

Customer	Reference tariff	Annual energy [kWh]	Peak [kW]
Residential Low Income	Lifeline	2 425	1.7
Residential Middle Income	Domestic	3 767	2.9
Residential High Income	Home User	5 510	4.3
Commercial	Small Power User	53 872	23.6
Industrial	Large Power User	2 380 077	650

The resulting archetypal load curves and the daily energy consumption are shown in the graphs below, showing both the profiles and the daily energy for each of the previously defined categories.

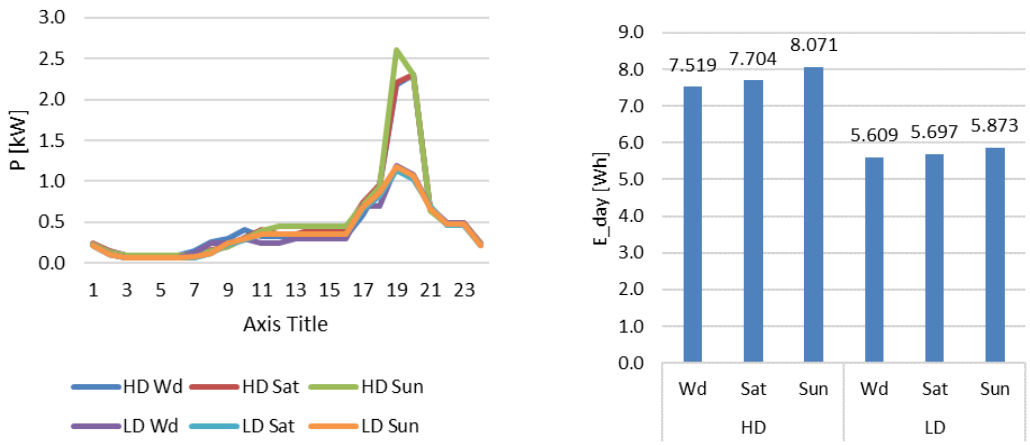


Figure 35: Residential low income load profile and daily energy output

[16] This step because the received profiles from the COCT were originally derived from aggregate measures performed at substation level. They therefore result to be 'averaged' and 'smoothed' by the diversity factor.
[17] Link: https://electrical-engineering-portal.com/demand-factor-diversity-factor-utilization-factor-load-factor.

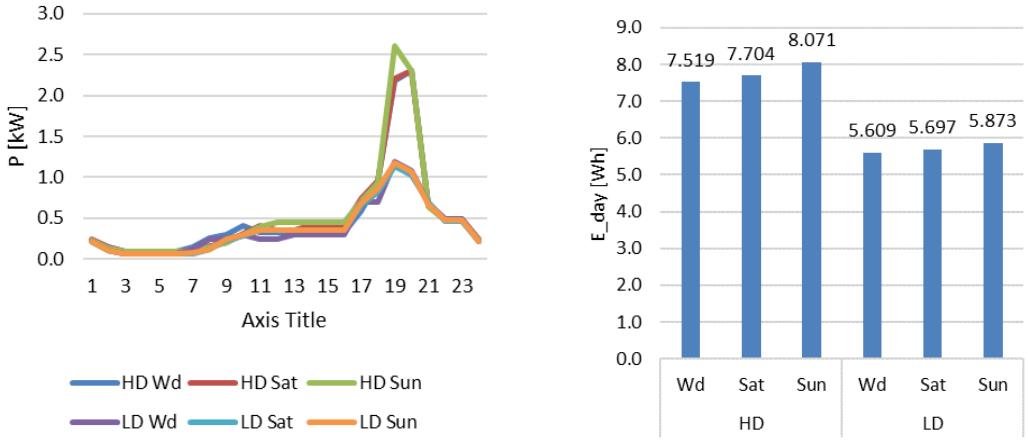


Figure 36: Residential middle income load profile and daily energy output

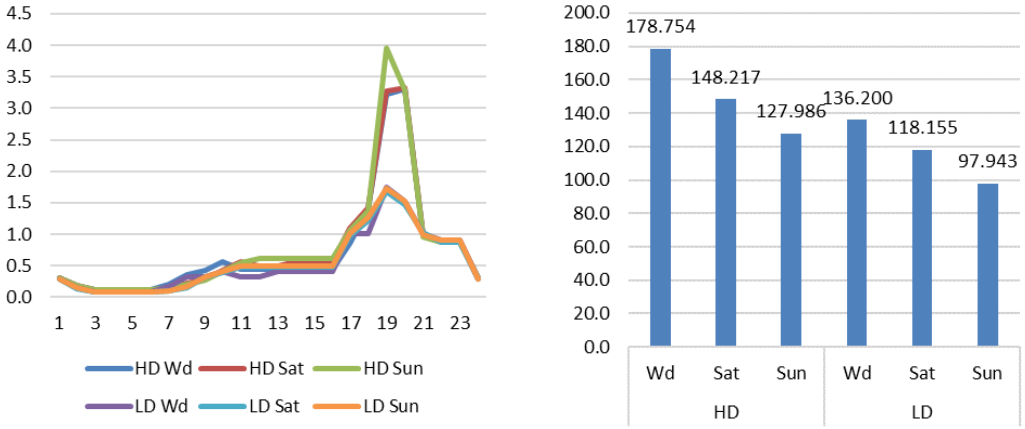


Figure 37: Residential high income load profile and daily energy output

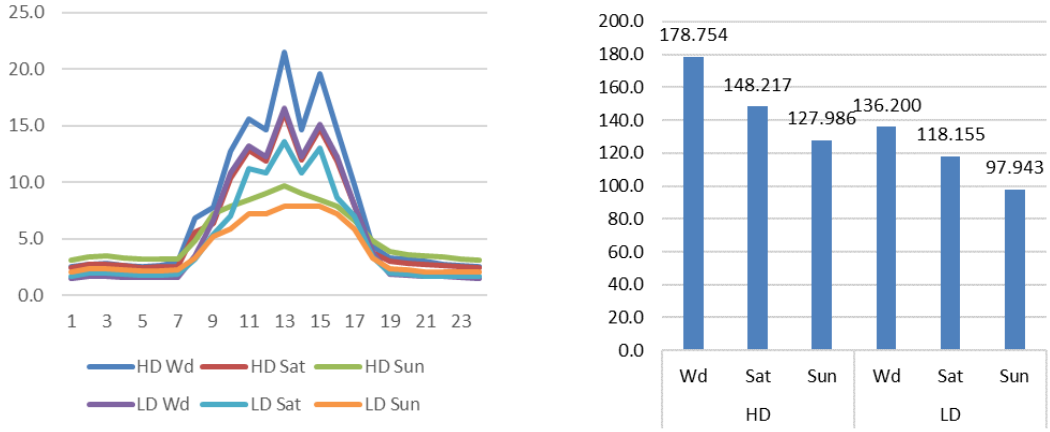


Figure 38: Commercial load profile and daily energy output

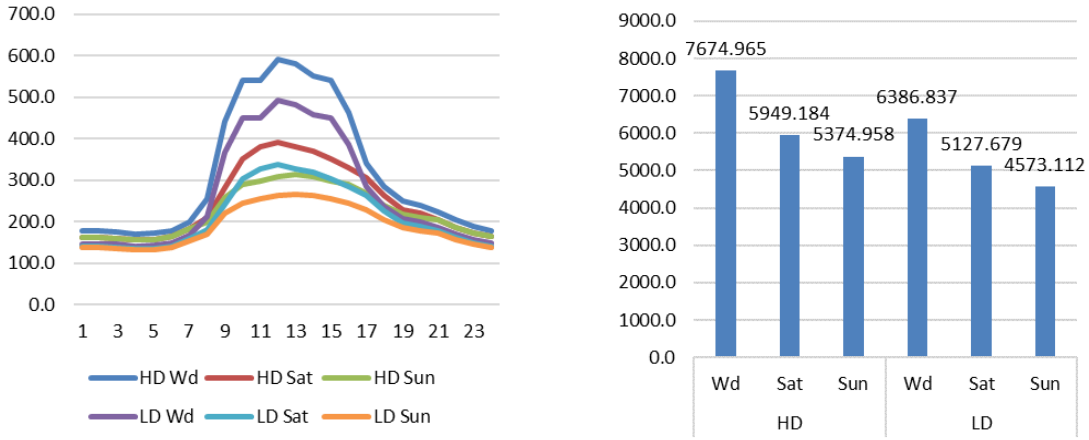


Figure 39: Industrial load profile and daily energy output

4.2.2.3. Electricity Tariffs

The *"Electricity Consumptive Tariffs_23_24"* file by COCT was used to determine the electricity price, related to the year 2023/2024. Since the PV and battery costs, detailed in the following paragraphs, include the VAT, the electricity tariff comprising the VAT was considered. Also, to perform the calculation, the average monthly consumption was extracted from the "Sales Summaries 23-24.xlsx" file. The input data are shown in the ***Table 24***.

The average electricity price [R/kWh], input to *MicroGridsPy* is calculated with the following formula:

$$Electricity\ price[R/kWh] = \frac{Service\ Charge + Energy\ Charge \cdot (Consumption - Free\ energy)/100}{Consumption}$$

In the industrial case – i.e. the large power tariff, since the identification of the corresponding tariff value was highly dependent on the industry characteristics, the average value from *"Sales Summaries 23-24"* was used instead.

Table 24: 23-24 Tariff data

Customer	Tariff	Consumption [kWh/month]	Service Charge [R]	Free energy [kWh]	Energy Charge [c/kWh]	Electricity price [R/kWh]
Residential Low Income	**Lifeline**	202.12	0	60	211.55	1.4875
Residential Middle Income	**Domestic**	313.56	0	0	350.80	3.5080
Residential High Income	**Home user**	459.19	252.09	0	308.58	3.6348
Commercial	**Small power**	4489.31	2838.3	0	269.78	3.33
Industrial	**Large power**	198,339.76	-	-	-	2.2881

Regarding the prices for selling surplus electricity to the grid, in case of Small-Scale Embedded Generation (SSEG) installations, the same *"Electricity Consumptive Tariffs_23_24"* file was used to extract the necessary data.

Table 25: Incentives output by customer

Case	Tariff [c/kWh]	Incentive [c/kWh]	Sell price [c/kWh]
Residential	100.05	28.75	128.80
Non residential	89.11	0.00	89.11

4.2.2.4. PV profiles

An annual hourly PV profile is created for each of the five selected types of customers, using open-source databases.

1. First, GHI data were downloaded from the Global Solar Atlas to for the Cape Town area to identify regions with average solar irradiation. The minimum GHI value observed across all zones was 1,538 kWh/m², which is above the typical threshold for effective solar energy generation (1,400 kWh/m2). Consequently, all zones within the municipality were deemed suitable for rooftop photovoltaic installations.
2. The mean GHI value for the Cape Town area was calculated to be 1,830 kWh/m².
3. A specific point on the map with a GHI value close to this mean was then identified to serve as a representative sample for further analysis, corresponding to a latitude of -34.021649° and a longitude equal to 18.441696°.

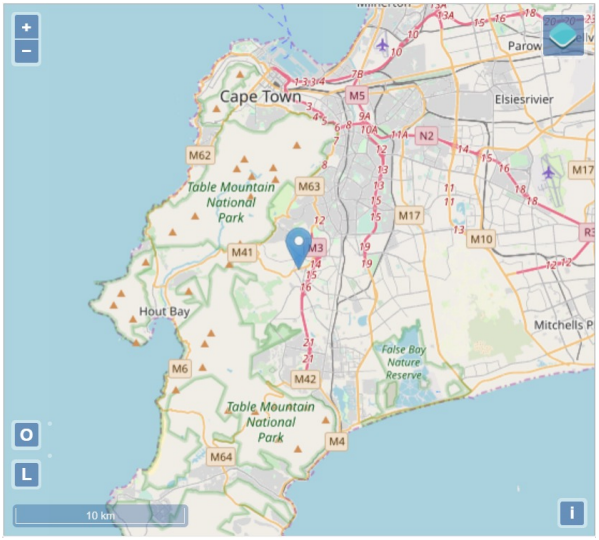


Figure 40: Location selected for the study

4. Using the identified point, ten hourly profiles were downloaded from PVGIS[18] (Photovoltaic Geographical Information System), to cover the possible different configurations of PV installations:
   - Optimal slope and azimuth, to reflect the case of installation at optimal conditions on flat buildings.
   - Average slope of tilted rooftops of residential[19] buildings and azimuth north, east and west.
   - Average slope of tilted rooftops of commercial buildings and azimuth north, east and west.
   - Average slope of tilted rooftops of industrial buildings and azimuth north, east and west.
5. The average slope of tilted rooftops was calculated in the Technical Potential and reported in Table 26. For each customer, the profiles related to the four different orientations and tilt angles are averaged according to the percentage of rooftop tiles belonging to each type, derived in the Technical Potential, to obtain a single profile. It is assumed that inclined rooftops are equally distributed among the three different orientations (North, East, West) and are tilted at the average slope of Cape Town rooftops.

Table 26: Slope and percentage of tilted and flat rooftop Usable Area

Customer	Average Slope (degrees)	Usable area-Flat	Usable area-Tilted North	Usable area-Tilted East	Usable area-Tilted West
Residential	26.09°	1%	33%	33%	33%
Commercial	22.84°	13%	29%	29%	29%
Industrial	17.57°	17%	28%	28%	28%

The results for a generation profile of 1000 W PV with 14% of Balance of System losses applied to a Residential case, is shown below in ***Figure 41***.

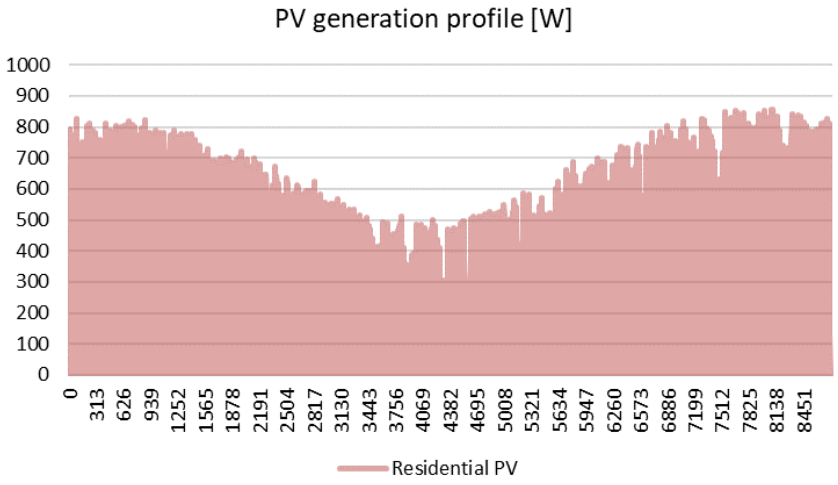


Figure 41: PV generation profile by customer

[18] *https://re.jrc.ec.europa.eu/pvg_tools/en/*
[19] *No distiction is made between High Income, Middle Income and Low Income in terms of rooftop slope and azimuth.*

Residential, Commercial and Industrial profiles are almost the same, with almost negligible variations in the peak and overall capacity factor (CF), as demonstrated in *Table 27*.

Table 27: PV generation profiles output parameters

Customer	CF	Peak
Residential	17.88 %	858 W
Commercial	17.93 %	876 W
Industrial	17.98 %	893 W

4.2.2.5. PV and battery costs

The costs of PV and BESS were determined using a bottom-up approach. A set of commercial PV-battery systems, identified by NTCSA as potential benchmarks for South Africa, were analyzed to establish the cost input data for the model. Specifically, the CAPEX input in *Microgridspy* were identified as follows:

- The **PV modules** cost [R/kW] for Residential Costumers is the average cost of the commercial modules reported in *Table 37* in *ANNEX C – COMMERCIAL REFERENCES FOR PV, BESS AND INVERTER COST ESTIMATION*.
- The **BESS** cost [R/kWh] for Residential Costumers is the average cost of the commercial BESS reported in *Table 38* in *ANNEX C – COMMERCIAL REFERENCES FOR PV, BESS AND INVERTER COST ESTIMATION*.
- Since *Microgridspy* does not model the inverter as an independent technology, the Inverter cost is entirely allocated to the PV modules. This assumption is motivated by the fact that in all the simulation scenarios, no BESS were installed without PV systems. The proportion of the inverter cost with respect to modules cost is retrieved from the prices of the commercial kit of PV+BESS systems (*Table 39* in *ANNEX C – COMMERCIAL REFERENCES FOR PV, BESS AND INVERTER COST ESTIMATION*).
- The **installation, cabling and other costs** related to PV and BESS systems were derived from the prices of the commercial solar kits, which report the details of all the cost items (*Table 40* in *ANNEX C – COMMERCIAL REFERENCES FOR PV, BESS AND INVERTER COST ESTIMATION*). The cost entries were allocated to the PV, or the BESS based on its function. PV modules cost was found to be 30% of the total cost (comprising the inverter), whereas the BESS represented the 68%.
- The total CAPEX of PV and BESS for Residential Costumers (*Table 28*), was computed as by dividing the average costs of the two technologies by the respective installation, cabling and other costs item.
- The CAPEX for of PV and BESS for Commercial and Industrial Customers were obtained assuming a reduction with respect to the Residential costs due to economies of scale: decrease of 10% in the cost of Commercial PV with respect to the Residential, and 10% for Industrial PV with respect to the Commercial.
- In MicroGridsPy, the PV cost includes the salvage value, whereas the battery cost does not. Given that the simulation covers only a one-year period, the battery cost needs to be adjusted to ensure comparability with the PV cost. To achieve this, a new battery cost was calculated that incorporates the salvage value:

1. First, the salvage value was calculated:

$$Salvage\ value_{BESS} = CAPEX_{BESS} \cdot \frac{(Lifetime_{BESS} - Lifetime_{Project})}{Lifetime_{BESS}} \cdot \frac{1}{(1+WACC)^{Lifetime_{Project}}}$$

where $Lifetime_{BESS} = 10$, $Lifetime_{Project} = 1$ and $WACC = 0.1$.

2. Then, the new specific cost was re-calculated by subtracting the salvage value:

$$CAPEX_{BESS}^{new} = CAPEX_{BESS} - Salvage\ value_{BESS}$$

- The results for all the types of customers are shown below in *Table 28*.

Table 28: PV and BESS CAPEX, input in Microgridspy

Case	PV CAPEX [R/W]	BESS CAPEX [R/Wh]	BESS CAPEX - Salvage [R/Wh]
Residential	12.71	5.57	1.013
Commercial	11.44	5.01	0.911
Industrial	10.30	4.51	0.82

4.2.2.6. Other simulation parameters

All the additional input parameters are listed in the *Table 29* below.

Table 29: Other simulation parameters by customer

Parameter	Residential	Commercial	Industrial	Source
PV O&M [Perc. Of CAPEX]	2%	2%	2%	CSIR
PV lifetime [years]	25	25	25	https://discovery.rubicon.tech/form
BESS roundtrip efficiency	86%	86%	86%	CSIR
BESS DOD	80%	80%	80%	https://discovery.rubicon.tech/form
BESS lifetime [years]	10	10	10	https://discovery.rubicon.tech/form
BESS cycles [#]	6000	6000	6000	https://discovery.rubicon.tech/form
BESS max. charge/ discharge	0.5 C	0.5 C	0.5 C	https://discovery.rubicon.tech/form
BESS O&M [Perc. Of CAPEX]	2%	2%	2%	NREL
WACC	10%	10%	10%	CSIR / https://sunbear.co.za/financing-your-solar-system-the-best-solar-financing-companies-in-south-africa/
Cost Alternative Energy Source* [R/kWh]	10	10	10	*corresponding to LCOE of diesel genset https://corporateandinvestment.standardbank.com/cib/global/insights/Big-energy-savings:-the-business-case-for-solar-investment

4.2.3. Step 3: PV Economically Viable Potential Estimation

4.2.3.1. Single-User results

The present chapter shows the results of MicroGridsPy simulation for all the 24 scenarios described in Step1: Model Setting. The tables report the optimal installed capacities for PV and BESS, the system costs, the energy parameters and the power exchanges between customers and the grid. Moreover, the dispatching profiles for 3 representative days are presented.

The tables below report the summary for the PV and BESS size results for each scenario. Some key points emerge:

- For all customers, the PV installed is lower in the Perfect Grid case with respect to the Load Shedding one, indicating that the current load shedding condition in the South African is contributing to PV installation as remedy measure to the frequent interruptions of the electricity supply service.
- In the residential high-income case, the different DoDs imply a difference in the results only in the Load Shedding case, whereas the Perfect Grid one shows no difference. This is a result of the fact that the 20%-DoD reflects the behavior of users highly sensitive to load shedding, which do not admit any hours of loss of supply, and therefore to an oversizing of the PV+BESS system.
- Regarding the BESS, the Perfect Grid case shows an always null installed capacity for all the customers, meaning that relying on an always available grid is more economically convenient than installing a storage system. The future trajectories of electricity grid tariffs could likely change the economic convenience of BESS.
- Differently from the PV size, the BESS installed in the Purchase only case is higher than the one installed in the Purchase/Sell scenario. This is a natural consequence of the fact that the lack of remuneration for PV surplus injected into the grid, it become convenient to install battery for valorizing the self-produced energy for self-consumption.
- Low-income customers, with lower electricity tariffs and likely less access to credit sources, do not see convenience in installing rooftop PV systems in a no-load shedding scenario. Also, the small sizes of the system in the load shedding cases are not expected to justify the investment of bi-directional meters and of the tariff change if they would apply to the SSEG programme.

Table 30: PV results summary

PV Results [kW]	Load Shedding		Perfect Grid	
	Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Residential high income – DoD 80%	1.6	1.19	1.16	0.78
Residential high income – DoD 20%	6.05	2.85	1.16	0.78
Residential middle income	1.11	0.83	0.8	0.55
Residential low income	0.14	0.14	0	0
Commercial	27.9	23.11	23.06	19.48
Industrial	880.81	764.55	658.39	562.61

Table 31: BESS results summary

BESS Results [kWh]	Load Shedding		Perfect Grid	
	Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Residential high income – DoD 80%	1.36	1.41	0	0
Residential high income – DoD 20%	49.61	52.46	0	0
Residential middle income	0.91	1.01	0	0
Residential low income	0.94	0.94	0	0
Commercial	69.18	72.81	0	0
Industrial	871.59	903.05	0	0

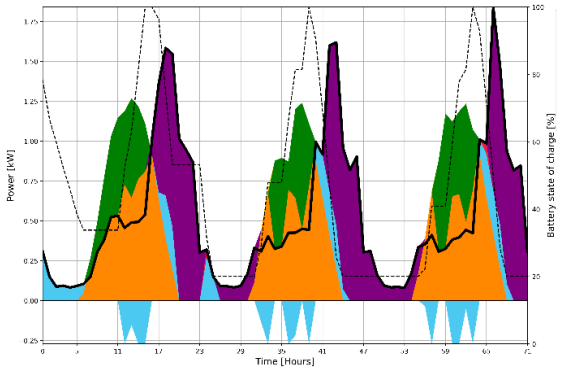
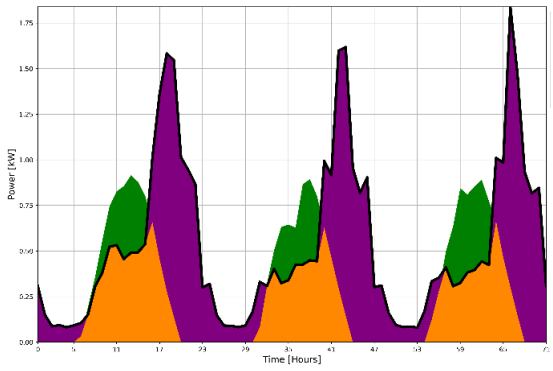
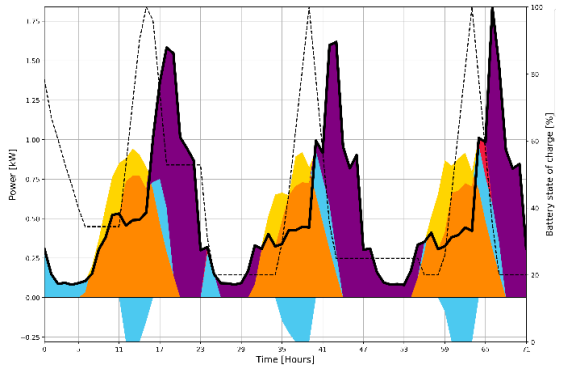
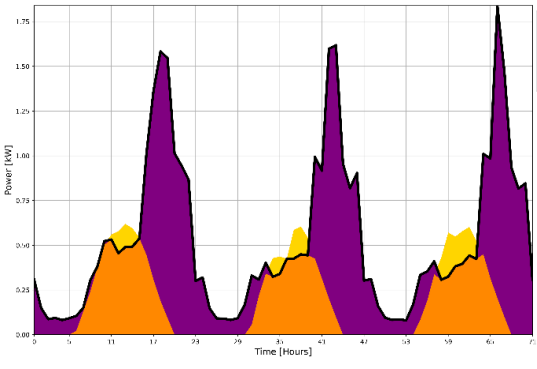
Analysing the overall results, the emerging key points are as follows:

1. *Energy supply*: For residential Customers (Perfect Grid Case), grid electricity effectively meets most of the load demand, especially during evening peak hours. In contrast, for commercial and industrial customers, peak demand aligns with midday hours when solar PV generation is highest, allowing PV to supply a significant portion of the load.
2. *Grid Impact*: in the *load-shedding* scenarios the installation of BESS reduces the peak power supplied by the grid only for Commercial customers, thanks to the good alignment of PV and load profiles. In the other scenarios, the peak power absorption is not reduced and, on the contrary, it does even increase for Middle and High income Residential and Industrial customers: in these cases, BESS needs to be fast charged to avoid loss of load during grid unavailability.
3. *Battery Contribution*: Battery energy provides a smaller share of total demand compared to PV or grid electricity in almost all the scenarios, indicating that it is a measure considered affordable and useful especially for reliability purposes, mainly.
4. *Grid Dependency*: Across all scenarios, grid electricity remains a constant source, indicating that a fully off-grid setup is generally neither practical nor efficient in South Africa.
5. *Demand-Response Potential*: Implementing effective demand-response strategies could help mitigate risks of oversizing due to load shedding, enhancing system efficiency.
6. *Costs*: the higher LCOE of the optimized system in the load shedding versus the perfect grid scenarios underlines the cost of load shedding experienced by the users, which are pushed to install solar and BESS systems for improving reliability. From a system planning perspective, grid reinforcements, eventually remunerated in tariff, should be carefully compared against the costs experienced by the single users in order to propose development plans that could maximize the overall benefits.

These points underscore the importance of optimizing grid, PV, and battery contributions based on customer type and usage patterns.

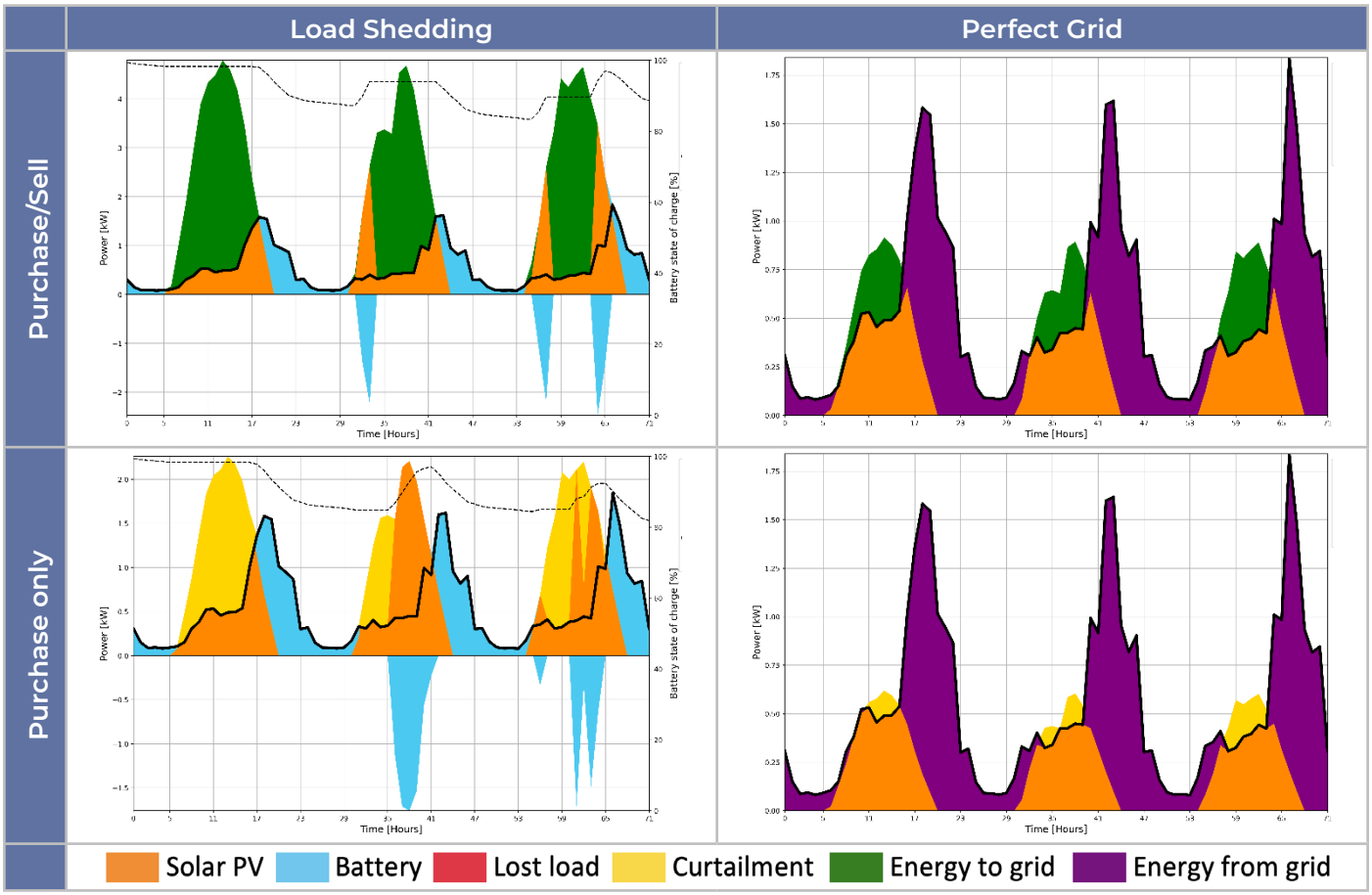
Case study: high income residential – DoD 80%

	Results	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Size	Size PV [kW]	1.60	1.19	1.16	0.78
	Size BESS [kWh]	1.36	1.41	0	0
Cost	Investment PV [kR]	20.371	15.136	14.684	9.935
	Investment BESS [kR]	7.575	7.854	0	0
	LCOE [R/kWh]	4.4	4.3	3.4	3.4
	Electricity tariff [R/kWh]	3.6	3.6	3.6	3.6
	Grid el. cost [kR]	9.325	10.07	12.549	13.344
	Grid el. revenues [kR]	0.563	0	0.475	0
Energy	Grid usage [%]	55.9	60.3	75.2	80.0
	Loss of load [%]	10.3	10.5	0	0
	Curtailment share [%]	2.4	10.7	0	9.75
	RES penetration [%]	44.9	35.9	30.4	21.8
	Battery usage [%]	6.7	6.7	0	0
Power	Peak load [W]	4 315	4 315	4 315	4 315
	Peak power from grid [W]	4 315	4 315	4 315	4 315
	Peak power to grid [W]	971	0	617	0
	Peak pow. from battery [W]	271	281	0	0
	Peak power to battery [W]	271	281	0	0

	Load Shedding	Perfect Grid
Purchase/Sell		
Purchase only		

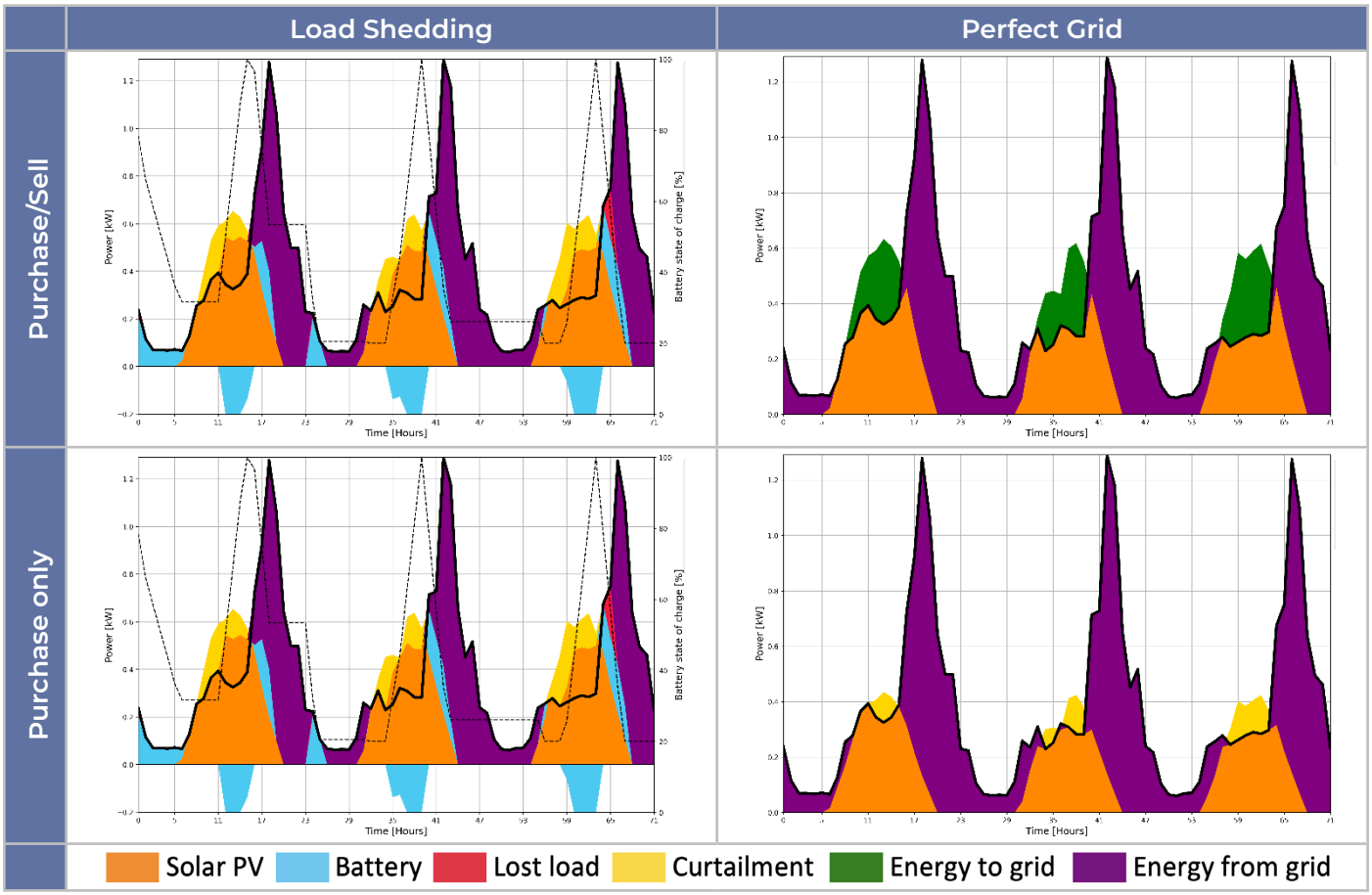
Case study: high income residential – DoD 20%

	Results	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Size	Size PV [kW]	6.05	2.85	1.16	0.78
	Size BESS [kWh]	49.61	52.46	0	0
Cost	Investment PV [kR]	76.951	36.284	14.684	9.935
	Investment BESS [kR]	276.328	292.202	0	0
	LCOE [R/kWh]	16.5	15.8	3.4	3.4
	Electricity tariff [R/kWh]	3.6	3.6	3.6	3.6
	Grid el. cost [kR]	2.12	5.275	12.549	13.344
	Grid el. revenues [kR]	4.542	0	0.475	0
Energy	Grid usage [%]	12.7	31.6	75.2	80.0
	Loss of load [%]	0	0	0	0
	Curtailment share [%]	0.2	8.7	0	9.8
	RES penetration [%]	93.1	72.0	30.4	21.8
	Battery usage [%]	47.9	36.1	0	0
Power	Peak load [W]	4 315	4 315	4 315	4 315
	Peak power from grid [W]	4 650	10 768	4 315	4 315
	Peak power to grid [W]	4 781	0	617	0
	Peak pow. from battery [W]	4 220	4 220	0	0
	Peak power to battery [W]	4 515	9 527	0	0



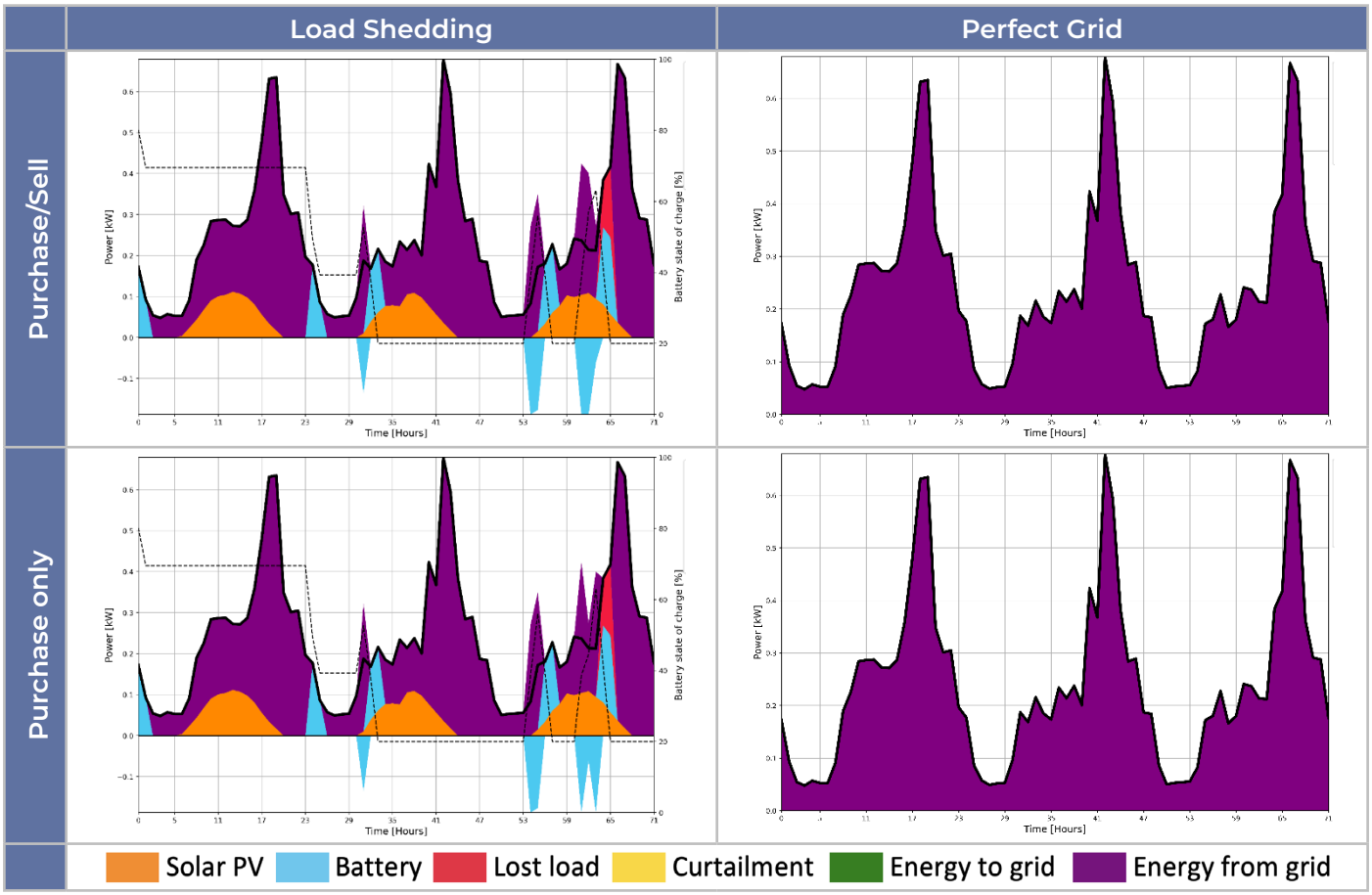
Case study: middle income residential

	Results	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Size	Size PV [kW]	1.11	0.83	0.8	0.55
	Size BESS [kWh]	0.91	1.01	0	0
Cost	Investment PV [kR]	14.07	10.496	10.164	6.984
	Investment BESS [kR]	5.069	5.626	0	0
	LCOE [R/kWh]	4.2	4.2	3.3	3.3
	Electricity tariff [R/kWh]	3.5	3.5	3.5	3.5
	Grid el. cost [kR]	6.085	6.609	8.159	8.704
	Grid el. revenues [kR]	0.367	0	0.301	0
Energy	Grid usage [%]	55.3	60.1	74.2	79.1
	Loss of load [%]	9.8	9.8	0	0
	Curtailment share [%]	2.3	9.0	0	8.8
	RES penetration [%]	45.5	36.4	31.0	22.4
	Battery usage [%]	6.6	7.0	0	0
Power	Peak load [W]	2 860	2 860	2 860	2 860
	Peak power from grid [W]	2 962	2 987	2 822	2 823
	Peak power to grid [W]	671	0	408	0
	Peak pow. from battery [W]	183	202	0	0
	Peak power to battery [W]	183	202	0	0



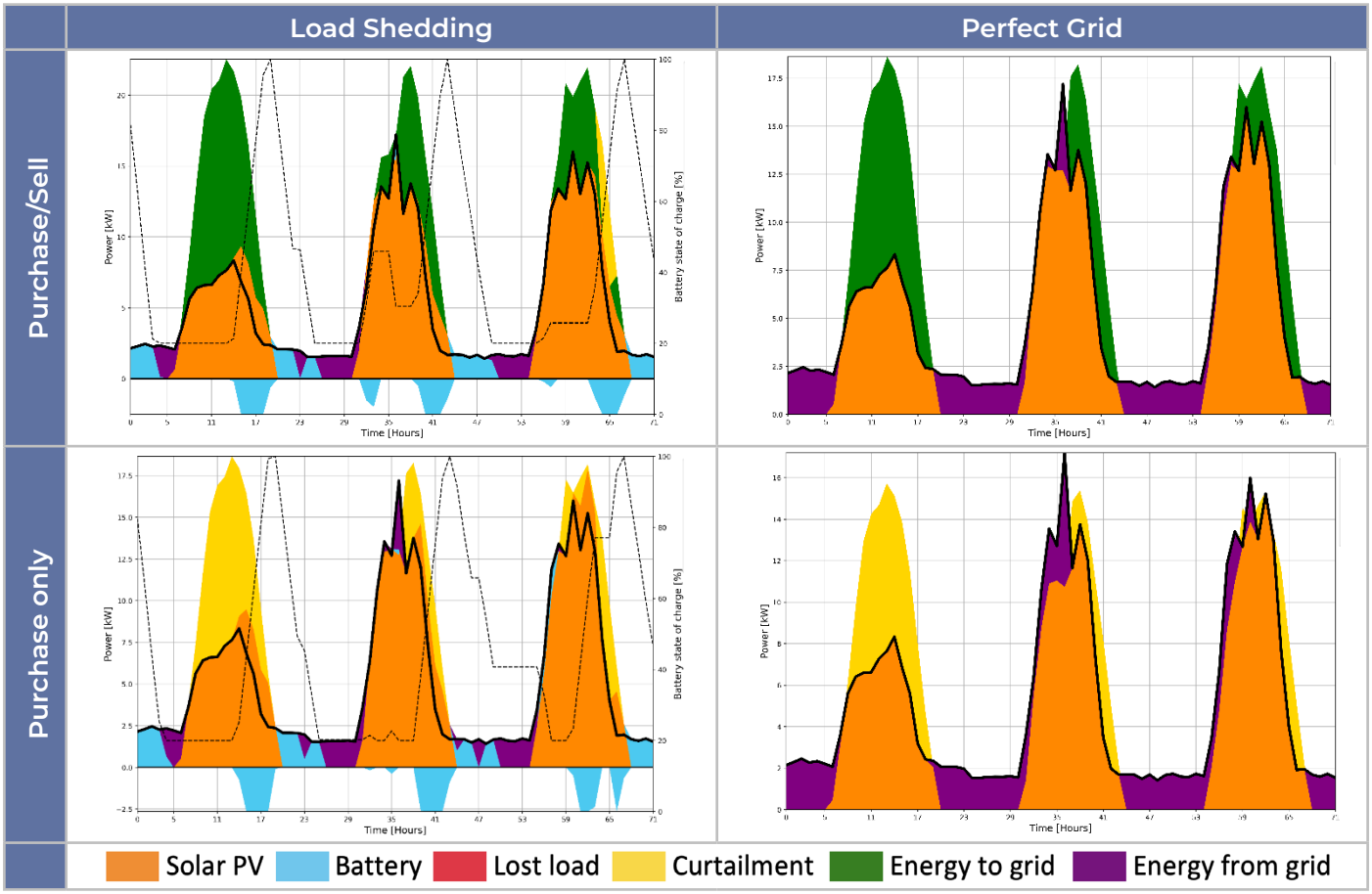
Case study: low income residential

	Results	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Size	Size PV [kW]	0.14	0.14	0	0
	Size BESS [kWh]	0.94	0.94	0	0
Cost	Investment PV [kR]	1.79	1.79	0	0
	Investment BESS [kR]	5.236	5.236	0	0
	LCOE [R/kWh]	2.8	2.8	1.5	1.5
	Electricity tariff [R/kWh]	1.5	1.5	1.5	1.5
	Grid el. cost [kR]	2.536	2.536	3.006	3.006
	Grid el. revenues [kR]	0	0	0	0
Energy	Grid usage [%]	84.4	84.4	100.0	100.0
	Loss of load [%]	8.1	8.1	0	0
	Curtailment share [%]	0	0	0	0
	RES penetration [%]	9.7	9.7	0	0
	Battery usage [%]	9.7	9.7	0	0
Power	Peak load [W]	1 713	1 713	1 713	1 713
	Peak power from grid [W]	1 840	1 840	1 713	1 713
	Peak power to grid [W]	0	0	0	0
	Peak pow. from battery [W]	188	188	0	0
	Peak power to battery [W]	188	188	0	0



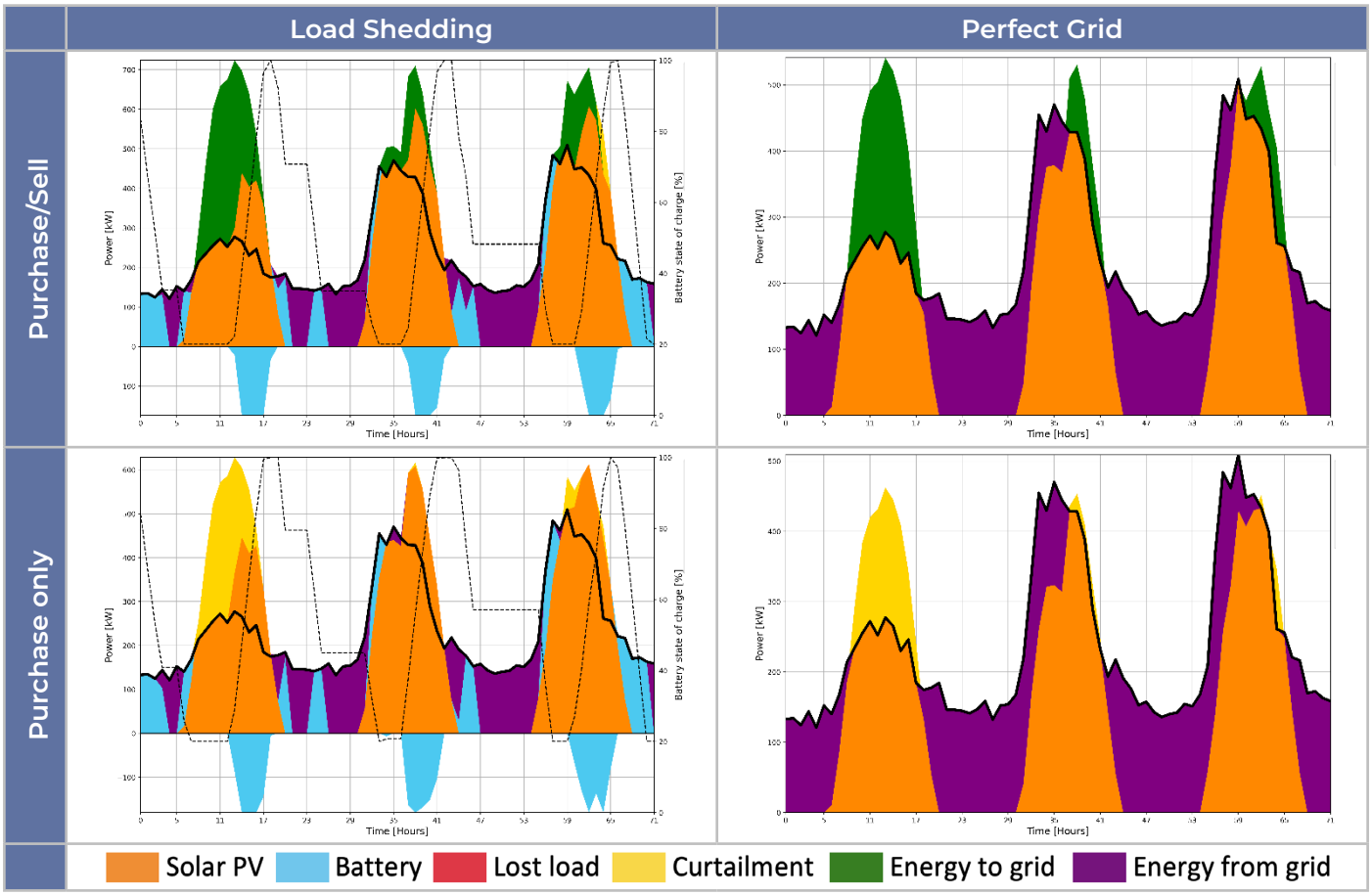
Case study: commercial

	Results	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Size	Size PV [kW]	27.9	23.11	23.06	19.48
	Size BESS [kWh]	69.18	72.81	0	0
Cost	Investment PV [kR]	319.228	264.332	263.853	222.867
	Investment BESS [kR]	346.592	364.778	0	0
	LCOE [R/kWh]	3.1	3.1	2.7	2.7
	Electricity tariff [R/kWh]	3.3	3.3	3.3	3.3
	Grid el. cost [kR]	49.861	57.488	65.603	73.174
	Grid el. revenues [kR]	5.617	0	4.452	0
Energy	Grid usage [%]	33.4	38.5	43.9	49.0
	Loss of load [%]	2.0	2.4	0	0
	Curtailment share [%]	2.0	10.6	0	10.1
	RES penetration [%]	70.9	63.7	60.5	53.7
	Battery usage [%]	6.8	7.1	0	0
Power	Peak load [W]	23 601	23 601	23 601	23 601
	Peak power from grid [W]	21 371	21861	21 197	21 405
	Peak power to grid [W]	17 309	0	13 067	0
	Peak pow. from battery [W]	2 516	2 649	0	0
	Peak power to battery [W]	2 516	2 649	0	0



Case study: industrial

	Results	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Size	Size PV [kW]	880.81	764.55	658.39	562.61
	Size BESS [kWh]	871.59	903.05	0	0
Cost	Investment PV [kR]	9 072.336	7 874.877	6 781.437	5 794.864
	Investment BESS [kR]	3 930.871	4 072.756	0	0
	LCOE [R/kWh]	2.6	2.6	2.1	2.1
	Electricity tariff [R/kWh]	2.3	2.3	2.3	2.3
	Grid el. cost [kR]	2 165.964	2 357.768	2 738.078	2 927.668
	Grid el. revenues [kR]	96.078	0	68.923	0
Energy	Grid usage [%]	47.7	52.0	60.3	64.5
	Loss of load [%]	1.5	1.5	0	0
	Curtailment share [%]	0.7	4.7	0	4.7
	RES penetration [%]	55.0	49.3	41.9	36.6
	Battery usage [%]	10.4	10.5	0	0
Power	Peak load [W]	650 020	650 020	650 020	650 020
	Peak power from grid [W]	738 191	747 766	575 689	584 113
	Peak power to grid [W]	525 054	0	328 937	0
	Peak pow. from battery [W]	174 319	180 609	0	0
	Peak power to battery [W]	174 319	180 609	0	0



4.2.3.2. Aggregated COCT Results

The results detailing total PV capacity (GW) and total energy generation (GWh) in the areas supplied by COCT based on the technical potential calculations are provided in *Table 32*. These energy values were derived by applying capacity factors, which were calculated for various user categories as outlined in Section 4.2.2.5.

Table 32: Results for total PV technical potential

Customer	PV CF	N customers [#]	Max PV capacity [kW]	Total PV capacity [GW]	Total energy [GWh]
Residential high income	17.88%	308,589	18	5.6	8501.5
Residential middle income		135,726	12	1.6	2492.8
Residential low income		162,079	6	1.0	1488.4
Commercial	17.93%	28,941	94	2.7	4175.4
Industrial	17.98%	1,406	1,177.40	1.7	2547.8

Table 33 and *Table 34* refer to the total PV capacity (GW) and total energy (GWh) respectively based on the economically viable potential calculations.

Table 33: Results for total PV capacity from economic potential evaluation

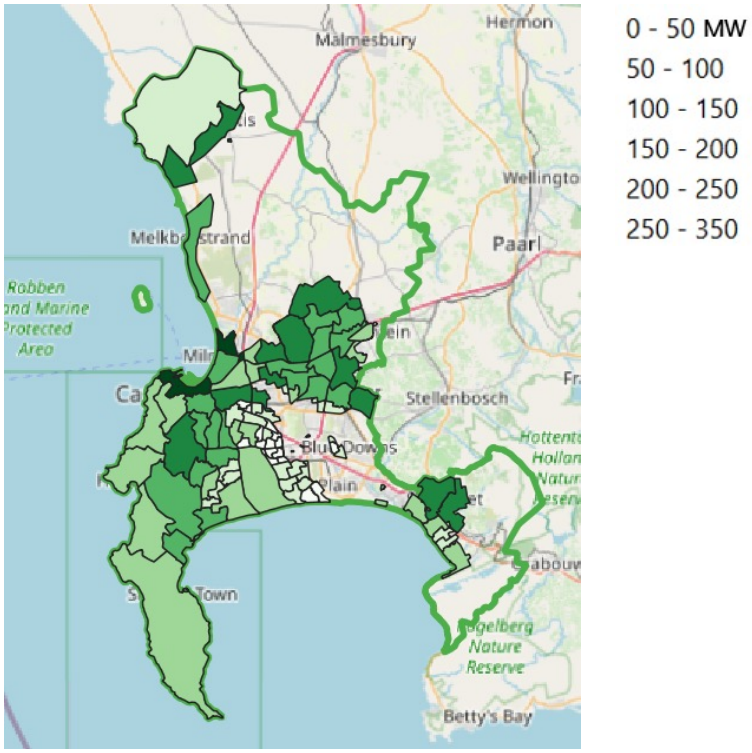
Total installed PV [MW]	N customers [#]	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Residential high income – DoD 80%	308,589	494	367	358	241
Residential high income – DoD 20%	308,589	1867	879	358	241
Residential middle income	135,726	151	113	109	75
Residential low income	162,079	23	23	0	0
Commercial	28,941	807	669	667	564
Industrial	1,406	1238	1075	926	791

Table 34: Results for total energy (GWh) from economic potential evaluation

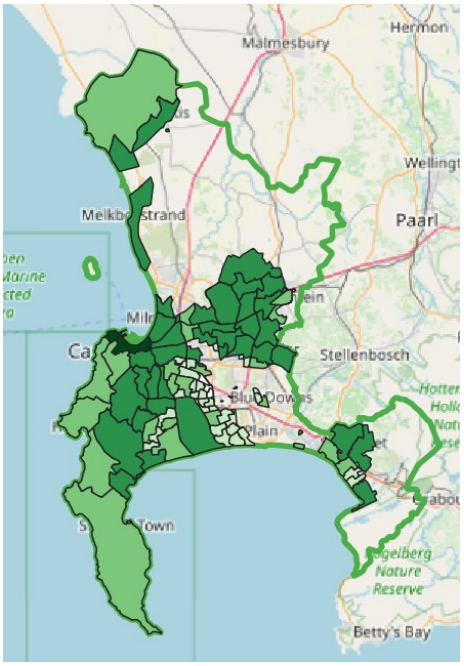
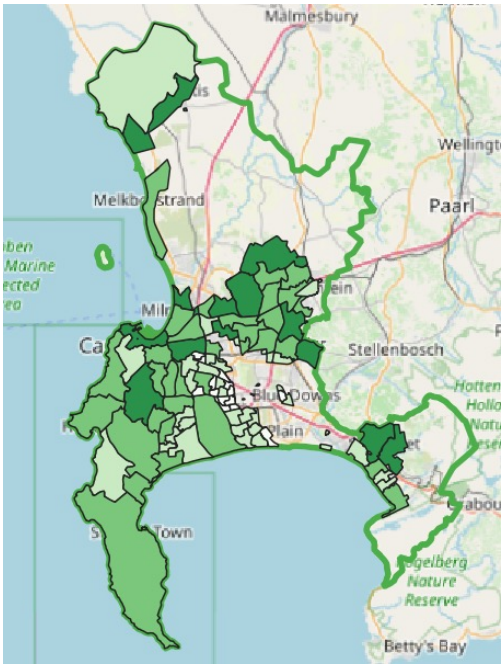
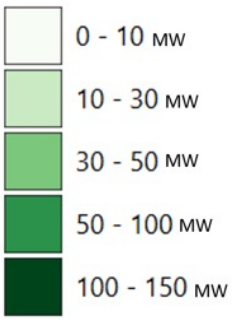
Total installed PV [MW]	N customers [#]	Load Shedding		Perfect Grid	
		Purchase/Sell	Purchase only	Purchase/Sell	Purchase only
Residential high income – DoD 80%	308,589	756	562	548	368
Residential high income – DoD 20%	308,589	2857	1346	548	368
Residential middle income	135,726	231	172	166	114
Residential low income	162,079	35	35	0	0
Commercial	28,941	1239	1027	1024	865
Industrial	1,406	1906	1654	1425	1217

Results for both technical and economic viable potential have been disaggregated per suburb, proportionally to the rooftop area of Residential, Commercial and Industrial buildings.

Table 35: Total PV technical potential per suburb



The capacity allocated to each suburb ranges from 1 MW in the smallest suburbs and the Perfect Grid (Purchase only) scenarios up to 120 MW in the central suburbs in the Load Shedding (Purchase/Sell).

Load Shedding: Purchase/Sell	Load Shedding: Purchase only	
		

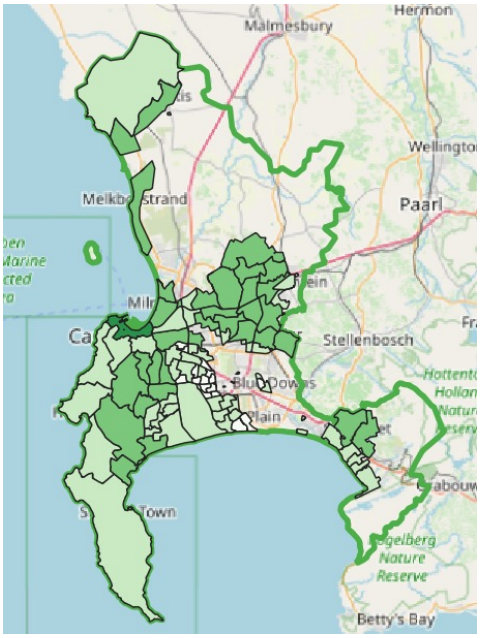
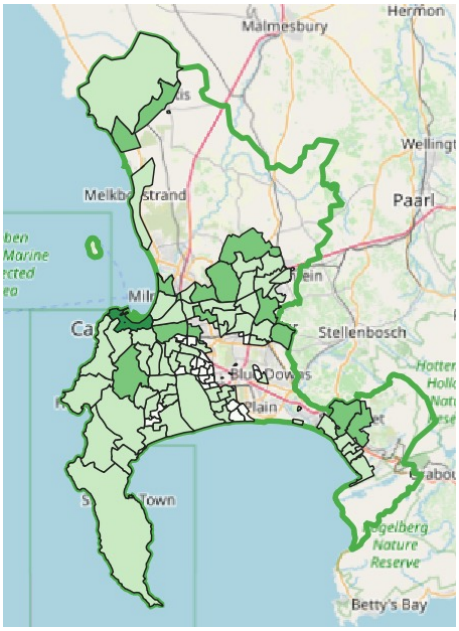
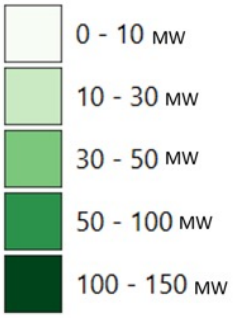
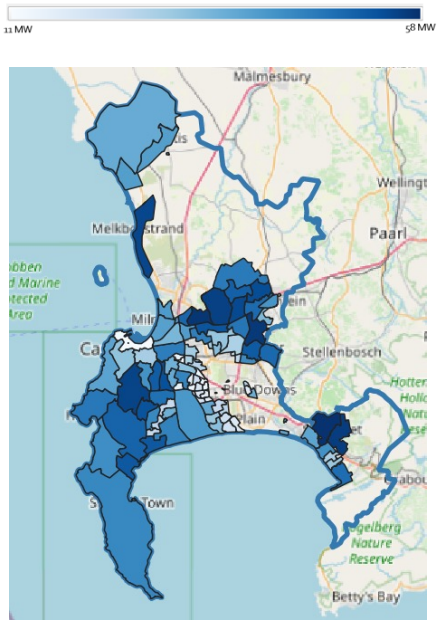
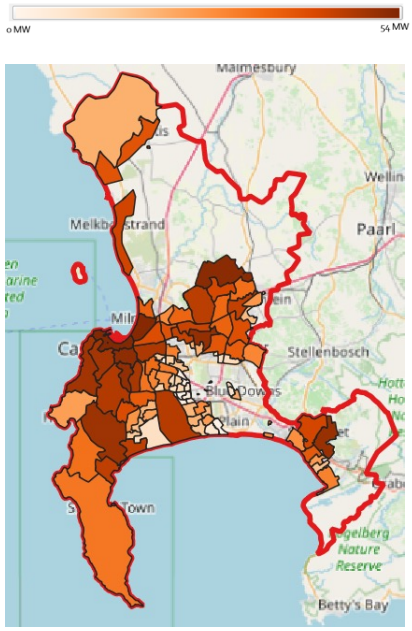
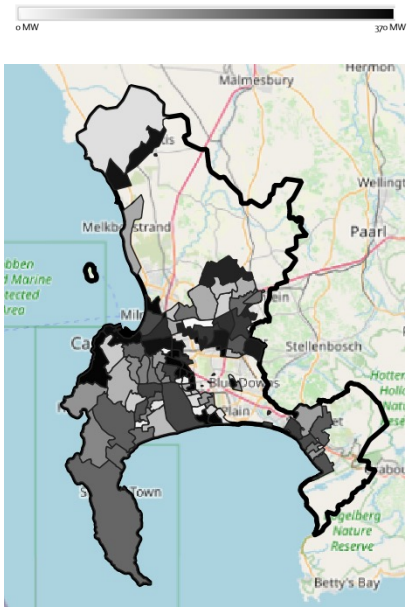
Perfect grid: Purchase/Sell	Perfect grid: Purchase only	
		

Table 36 reports the total PV capacity per suburb and per type of customer in the case of Load Shedding (Purchase/Sell) scenario.

Table 36: Total PV capacity per suburb and per type of customer

Total PV capacity Residential customers per suburb	Total PV capacity Commercial customers per suburb	Total PV capacity Industrial customers per suburb
		

5. CONCLUSION

This study aims at enhancing NTCSA's planning and grid operating efforts by enabling more accurate forecasting of the future potential of rooftop PV and BESS in South Africa. This is done by building upon the development of a robust methodology for assessing and modelling the technical and Economically Viable Potential of rooftop PV and BESS installations in the country. The methodology consists in two (2) phases, namely the Technical and the Economically Viable Potential analyses, including an overview on state-of-the-art models and tools:

1. In Phase 1, the Technical Potential stands upon the elaboration of GIS data and the identification of archetypal users to calculate the rooftop characteristics and maximum rooftop space available for rooftop solar installations and identify the maximum PV size that could be installed on a certain building stock.
2. In Phase 2, Economically Viable Potential identifies the expected maximum PV and battery capacities that customers may be willing to install to reach the economic optimum or satisfy reliability requirements, given a set of input data and constraints regarding energy balances, technical characteristics, costs, tariffs and available space. The methodology gives in output the optimal sizes of PV and BESS systems that each archetype user can install to supply the load demand according to different scenarios and sensitivities, and the hourly energy balances and exchanges with the national grid. Results for each archetypical user type can be then aggregated to cover any given study area (from municipality up to country level).

The methodology is tested in a quantitative Proof-of-Concept to the Cape Town Municipality, offering insights into possible outcomes and scenarios that NTCSA can later replicate across other regions with varying assumptions and boundaries.

In the POC, we categorized each building and possible prosumer as Residential, Commercial and Industrial. The main numerical results are the following:

- From the single-user perspective, the Technical Potential ranges from 6 to 18 kW for residential users, depending on the wealth status (low income, middle income, high income), 470 kW for Commercial, and almost 6 MW for Industrial users. From an aggregated standpoint, this leads to an aggregated Technical Potential of 12.6 GW (19 206 GWh/yr) for the Municipality of Cape Town.
- Concerning the Economically Viable Potential, single-users and aggregated results vary according to the proposed scenarios, which considers conditions of *with* vs *without* load shedding, *with* vs *without* the possibility to sell the excess power to the grid.

The results offer the following conclusions

- For all customers, the PV installed is lower in the case *without* load shedding with respect to the *with* load shedding one, indicating that the current load shedding condition in the South Africa is contributing to PV installation as remedy measure to the frequent interruptions of the electricity supply service.
- Regarding the BESS, the case *without* load shedding shows an always null installed capacity for all the customers, meaning that relying on an always available grid is more economically convenient than installing a storage system.
- Differently from the PV size, the BESS installed in the case *without* the possibility to sell excess power is higher than the one installed in the case *with* the possibility to sell excess power. This is a natural consequence of the fact that due to the lack of remuneration for PV surplus injected into the grid, it becomes convenient to install battery for valorizing the self-produced energy for self-consumption.

SINGLE-USER RESULTS				
PV Results [kW]	*with* Load Shedding		*without* Load Shedding	
	with selling excess power	*without* selling excess power	*with* selling excess power	*without* selling excess power
Residential high income	1.6 (6.05)	1.19 (2.85)	1.16 (1.16)	0.78 (1.16)
Residential middle income	1.11	0.83	0.8	0.55
Residential low income	0.14	0.14	0	0
Commercial	27.9	23.11	23.06	19.48
Industrial	880.81	764.55	658.39	562.61
BESS Results [kWh]	Load Shedding		Perfect Grid	
	with selling excess power	*without* selling excess power	*with* selling excess power	*without* selling excess power
Residential high income	1.36 (49.61)	1.41 (52.46)	0 (0)	0 (0)
Residential middle income	0.91	1.01	0	0
Residential low income	0.94	0.94	0	0
Commercial	69.18	72.81	0	0
Industrial	871.59	903.05	0	0
() the values in brackets represent the case of a very precautionary and non-optimized use of the battery, which is kept always at least 80% charged to reduce to 0 the risk of having unmet demand due to load shedding.				

AGGREGATED RESULTS (Municipality level)				
PV Results [kW]	*with* Load Shedding		*without* Load Shedding	
	with selling excess power	*without* selling excess power	*with* selling excess power	*without* selling excess power
Residential high income	494 (1867)	367 (879)	358 (358)	241 (241)
Residential middle income	151	113	109	75
Residential low income	23	23	0	0
Commercial	807	669	667	564
Industrial	1238	1075	926	791
BESS Results [kWh]	Load Shedding		Perfect Grid	
	with selling excess power	*without* selling excess power	*with* selling excess power	*without* selling excess power
Residential high income	756 (2857)	562 (1346)	548 (548)	368 (368)
Residential middle income	231	172	166	114
Residential low income	35	35	0	0
Commercial	1239	1027	1024	865
Industrial	1906	1654	1425	1217
() the values in brackets represent the case of a very precautionary and non-optimized use of the battery, which is kept always at least 80% charged to reduce to 0 the risk of having unmet demand due to load shedding.				

In terms of overall conclusion, the emerging key points are as follows:

1. *Battery Contribution*: Battery energy provides a smaller share of total demand compared to PV or grid electricity in all the scenarios, indicating that it is predominantly a measure considered affordable and useful for reliability purposes, mainly.
2. *Grid Impact*: PV + BESS systems in load-shedding scenarios could in some cases lead to an increase of peak power absorbed from the grid. The regulatory framework, comprising size and currents limitation for SSEG systems (e.g. (COCT, 2023)), has an important role in promoting the integration of distributed resources while limiting their impact on the grid.
3. *Grid Dependency*: Across all scenarios, grid electricity remains a constant source, indicating that a fully off-grid setup is generally neither practical nor efficient in South Africa.
4. *Demand-Response Potential*: Implementing effective demand-response strategies could help mitigate risks of oversizing due to load shedding, enhancing system efficiency.
5. *Costs*: The higher Levelized Cost of Energy (LCOE) in the optimized system under load-shedding conditions, compared to perfect-grid scenarios, highlights the cost burden that load shedding imposes on users. This situation drives users to install solar and Battery Energy Storage Systems (BESS) to enhance reliability. From a system planning perspective, the costs of grid reinforcements, which may ultimately be remunerated in tariffs, should be carefully weighed against the individual costs incurred by users. This comparison is essential to propose development plans that maximize overall benefits and balance reliability improvements across the grid.

These points underscore the importance of optimizing the grid in tandem with the anticipated contributions from rooftop PV and battery storage, as both elements are mutually dependent. By accurately forecasting and integrating these decentralized resources into planning models, NTCSA can improve the efficiency and reliability of the grid. This optimization not only supports grid stability but also creates a favourable environment for the expansion of the V-RES IPP sector, providing a pathway for sustainable energy growth in South Africa.

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7. ANNEX A –PROCEDURES

The present Annex details the input data and the necessary steps useful to replicate the procedure in different sites of interests or with different scenarios and assumptions.

The procedures described below are maintained by RES4Africa and NTCSA. Readers seeking further details are encouraged to consult them directly.

7.1. INPUT DATA AND SURVEYS

The input data used in the Proof of Concept are detailed in Section 4 and delivered to NTCSA as GIS layers, *.csv* and *.xlsx* files. NTCSA could directly use those or recreate the inputs, using the same format and different hypotheses and base data.

For facilitating the data collection process, two questionnaires have been developed:

1. *Res4Africa Solar Data Collection.xlsx*: it is very detailed and could be delivered to representatives of key associations working in the rooftop PV sector. It is divided into 8 sections, covering the items described in Paragraph 3.1.
2. *GoogleForm*: it is a simplified form, that could be delivered to a wider plethora of technicians, e.g. rooftop PV installers, with direct on-field experience. The link for the compilation is the following: https://docs.google.com/forms/d/e/1FAIpQLSdOAL1cpjiCHt1cYE9NPEUto1S-xNzbub4yMDOd7Id7VgbfKg/viewform?usp=sharing

7.2. TECHNICAL POTENTIAL PROCEDURE

The detailed steps for implementing the Technical Potential evaluation are outlined in the two procedures:

1. *ARCGIS procedure (with DSM): Procedure_withDSM.xlsx*
2. *QGIS procedure: Procedure_withoutDSM.xlsx*

Those procedures are built in Excel to calculate the Technical Potential of installable PV systems on rooftops. These procedures differ in their use of a DSM (Digital Surface Model) layer, which impacts how the slope and shading of rooftops are assessed. Both approaches take as input data the building footprint information, land cover classification, and Enumeration Areas (EA) classification (if available). The objective is to estimate key metrics such as the average rooftop slope, usable area for PV installation, and the total gigawatt capacity that can be installed across different customer types (residential, commercial, and industrial). The procedure without the DSM layer uses **QGIS**, while the one that incorporates the DSM layer relies on **ArcGIS** for more detailed analysis.

The Procedure_withoutDSM.xlsx does not use a DSM layer and it should be applied when the DSM of the selected area is not available. In this case the estimation of rooftop slopes as well as the area reduction coefficients is based on general assumptions drawn from literature or considering extendable results from this study on Cape Town municipality to the whole South African territory.

The Procedure_withDSM.xlsx involves the use of a DSM layer, which significantly enhances the accuracy of the calculations. As in the first method, the total rooftop area is calculated from the building footprint data. However, instead of relying on assumed slope values, using ArcGIS functions from the DSM layer it is possible to obtain detailed elevation data for the area, allowing for a direct and accurate calculation of each rooftop's slope. This enables a more precise assessment of rooftop suitability for PV installation. Additionally, the DSM layer allows for a detailed shading and orientation analysis, further refining the estimation of the usable area.

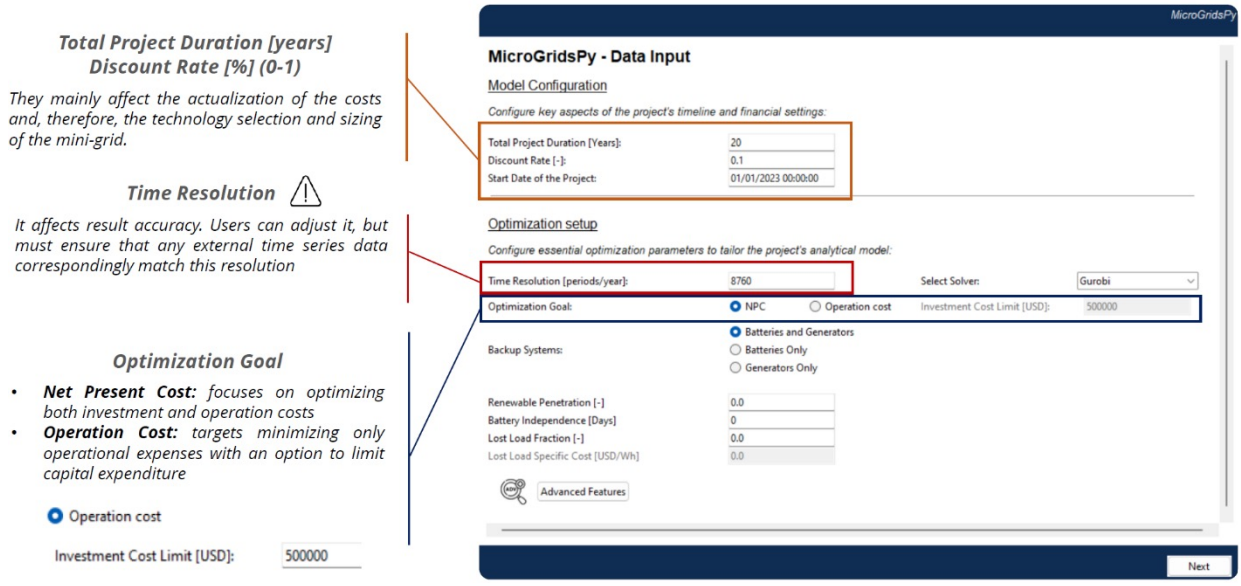
7.3. ECONOMICALLY VIABLE POTENTIAL PROCEDURE

The Economically Viable Potential evaluation is based on optimization performed with the *MicrogridsPy* tool, developed by Politecnico di Milano. It is a python-based tool that can be downloaded at the following link, following the instructions present on the GitHub page: https://github.com/SESAM-Polimi/MicroGridsPy-SESAM. The documentation is detailed and provides instructions for running the model: https://microgridspy-docs.readthedocs.io/en/latest/.

MicroGridsPy comprehends a graphical user interface (GUI) organized into specialized pages to define and input the data and parameters of the model. This first window allows to configure the key aspects of the project's timeline and financial settings, such as:

- Total duration of the project.
- Discount rate.
- Time resolution in periods per year.
- Optimization goal between Net Present Cost and operation cost.

The following sections show screenshots taken by the official MicroGridsPy documentation and summarize the official technical guide of the model.

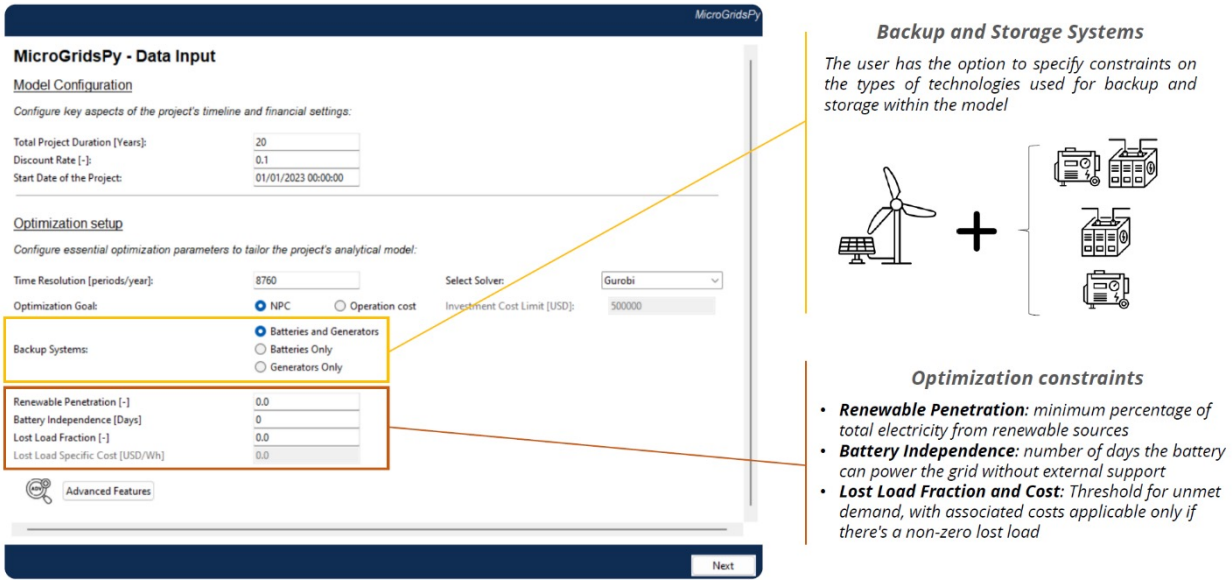


The users can also set constraints on the types of technologies used for backup and storage within the model, enabling the selection among:

- Batteries and Generators.
- Batteries only.
- Generators only.

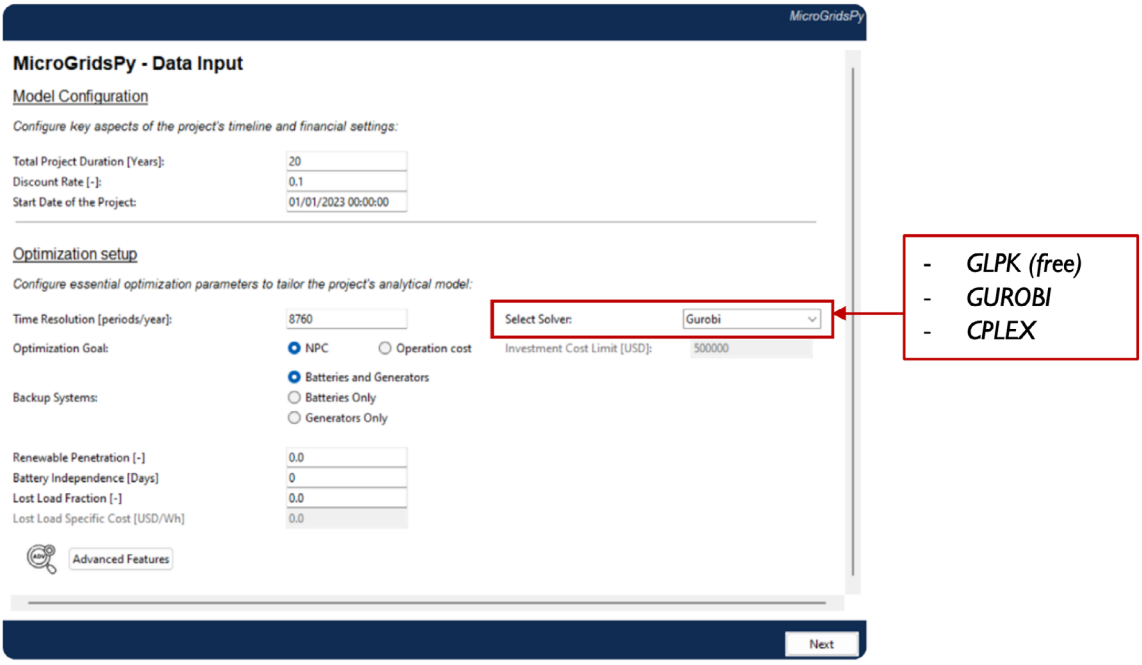
Moreover, the GUI allows users to set other optimization constraints:

- Renewable Penetration sets the minimum percentage of total electricity that must come from renewable sources.
- Battery Independence indicates the number of days the battery storage system can power the grid without external support.
- Lost Load Fraction and Cost defines the threshold for unmet demand, along with associated costs that apply only if there is a nonnull lost load.



In the first window it is possible to select also which solver will be used to solve the optimization proble. Three solvers are currently available and integrated in MicroGridsPy:

- GLPK (GNU Linear Programming Kit) is an open-source solver that is suitable for solving small to medium-sized optimization problems.
- Gurobi is a commercial solver known for its high performance and speed, making it ideal for academic and professional use where large-scale optimization tasks are involved. Although it requires license activation, Gurobi is free for academic use, and installation instructions can be obtained from the official Gurobi website.
- Cplex is a powerful optimization software package designed to solve various types of mathematical optimization problems, including linear, mixed-integer, and quadratic programming.



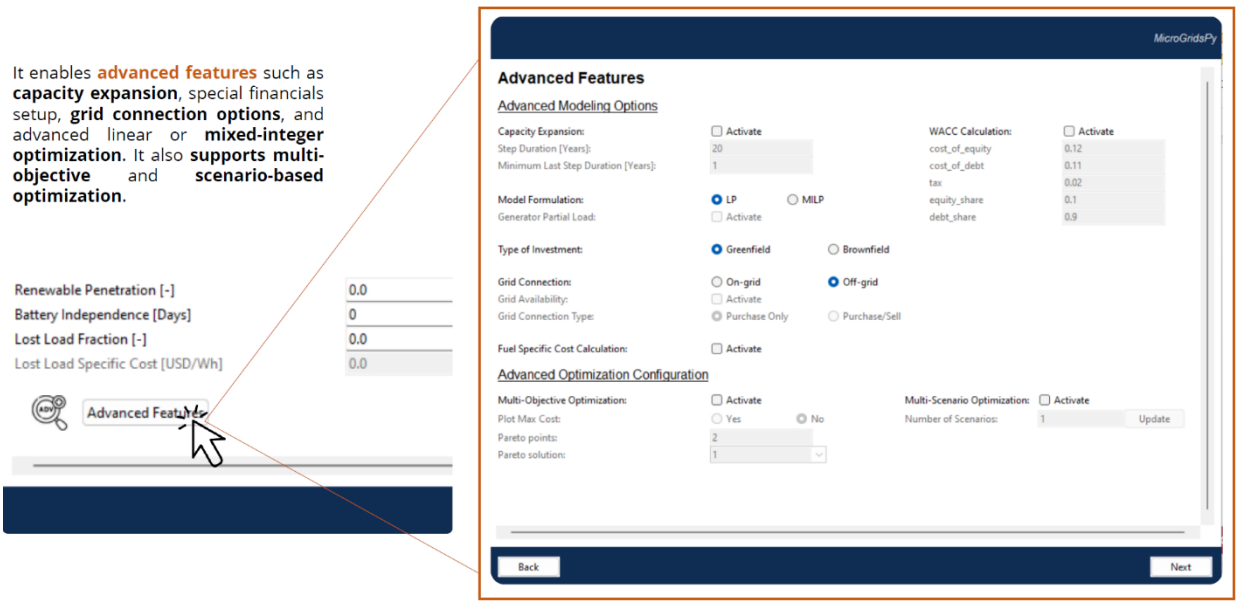
Clicking the «Advanced Features» button the GUI provides enhanced modelling options. When it comes to the problem formulation, the options are as follows:

- Linear Programming (LP) provides a simplified, continuous representation of operations, ideal for scenarios where decisions do not need to be binary.
- Mixed-Integer Linear Programming (MILP) incorporates integer variables, allowing for a unit commitment approach that can handle on/off decisions and more complex relationships, crucial for discrete decision-making processes like those found in many energy systems.

On the other hand, a set of grid options can be selected:

- On-grid vs. Off-grid determine whether the microgrid will be connected to a larger grid or operate independently,
- Grid Availability can be activated if grid availability is variable and should be considered in the model.
- Grid Connection Type offers a choice between purchase-only or the ability to both purchase and sell electricity, reflecting the microgrid's interaction with the main grid.

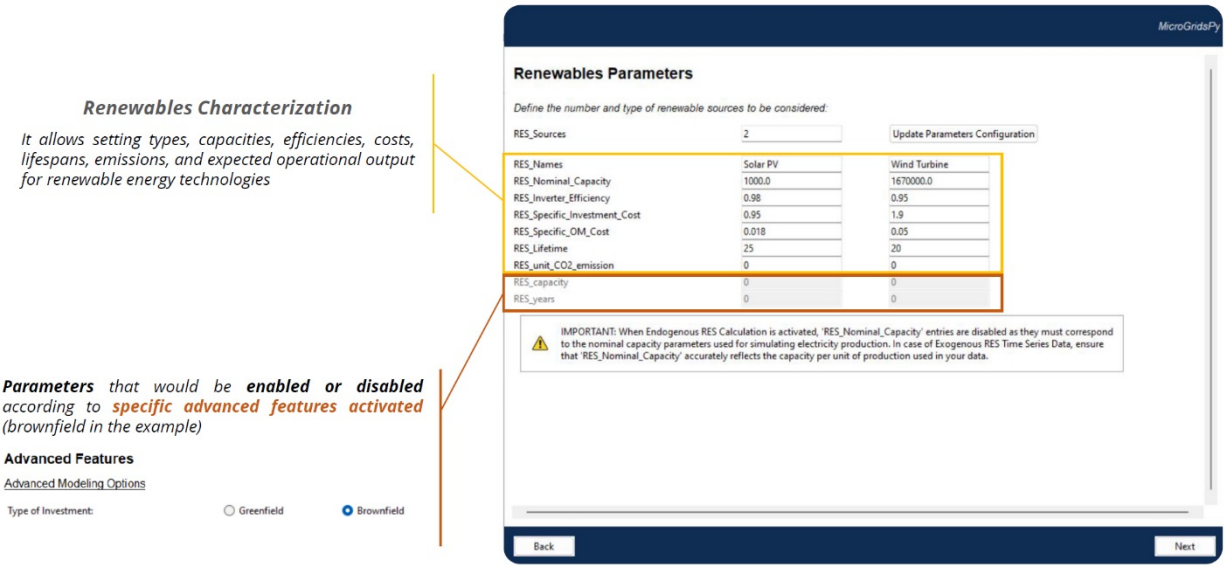
Lastly, the Multi-Objective Optimization can be selected to also consider the emissions in the objective function: it provides a mechanism to build a Pareto Curve, which represents various trade-offs between cost and emissions. Users can select the number of Pareto points to analyse, allowing them to explore the spectrum of solutions from minimizing emissions to minimizing costs. The interface also enables users to choose and display a specific solution on this curve.

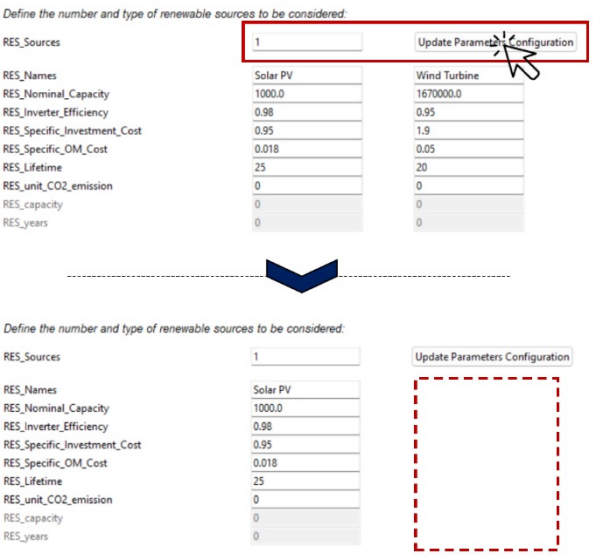


In the Renewable Energy Sources (RES) window, users can specify solar PV parameters to accurately model solar generation potential. These parameters include:

- Nominal power: The power rating of the solar panels.
- Tilt angle: The angle at which the panels are tilted relative to the horizontal.
- Azimuth: The orientation of the panels (e.g., facing south, east, etc.).
- Efficiency-related coefficients: Factors affecting solar panel efficiency.

Also, the RES_Sources field allows users to set the number and types of renewable sources. For each selected technology different parameters can be configured. The interface includes an «Update Parameters Configuration» button, which applies new settings to the renewable energy sources. After adjusting the necessary parameters and specifying the number of renewable sources, pressing this button will update the system with the latest configurations.



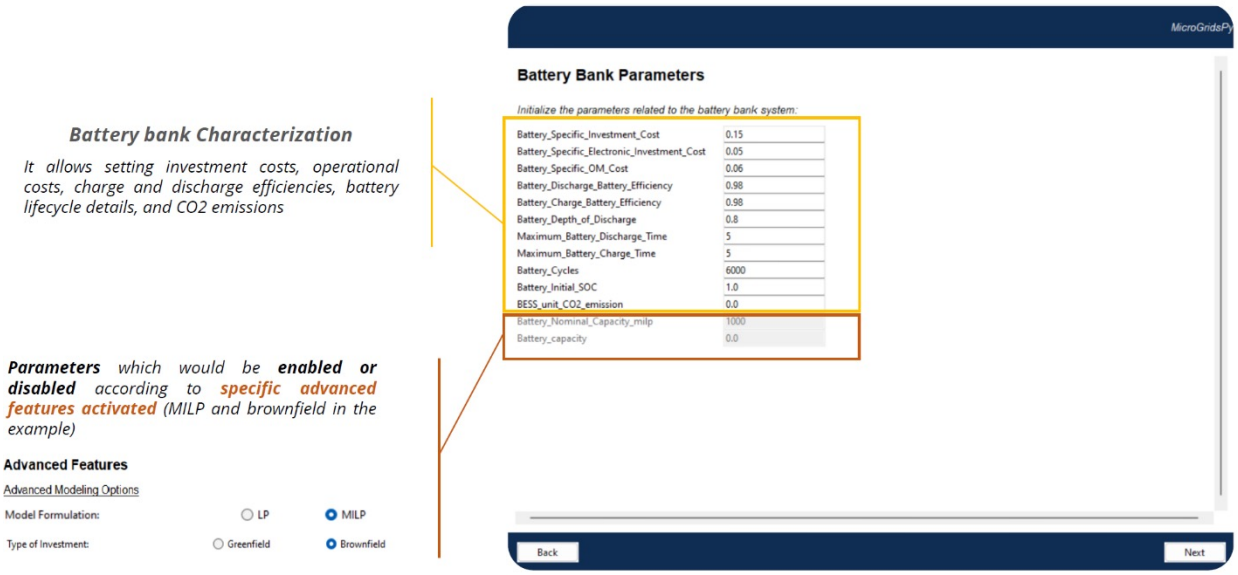


The interface includes an "**Update Parameters Configuration**" button for applying new settings to renewable energy sources. In particular:

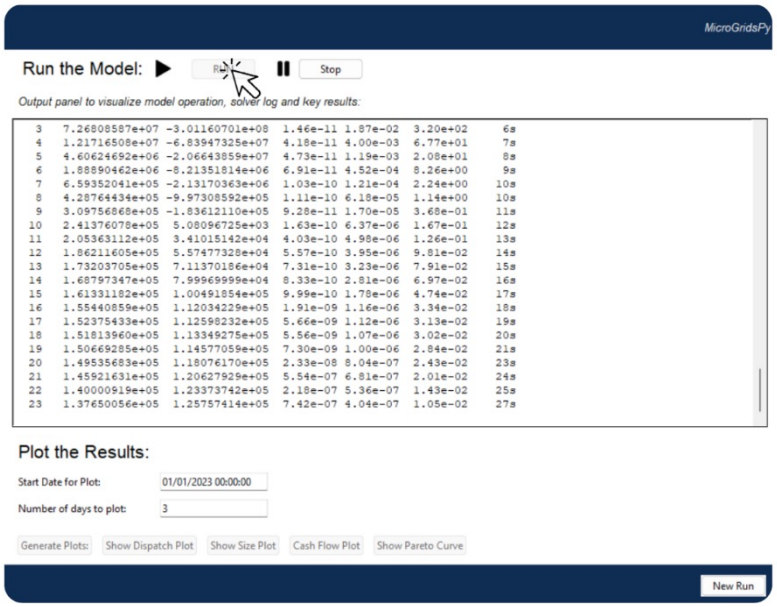
1. Set the number of renewable sources in **RES_Sources**
2. **Press the button** to update the entries for each parameter
3. Visualize the **new set of default values** for each parameter
4. **Edit** the values as preferred

The Storage System Characterization interface facilitates the definition of battery bank parameters. Within this section, users can input key parameters related to battery systems such as:

- Investment costs.
- Operational costs.
- Efficiencies.
- CO2 emissions.



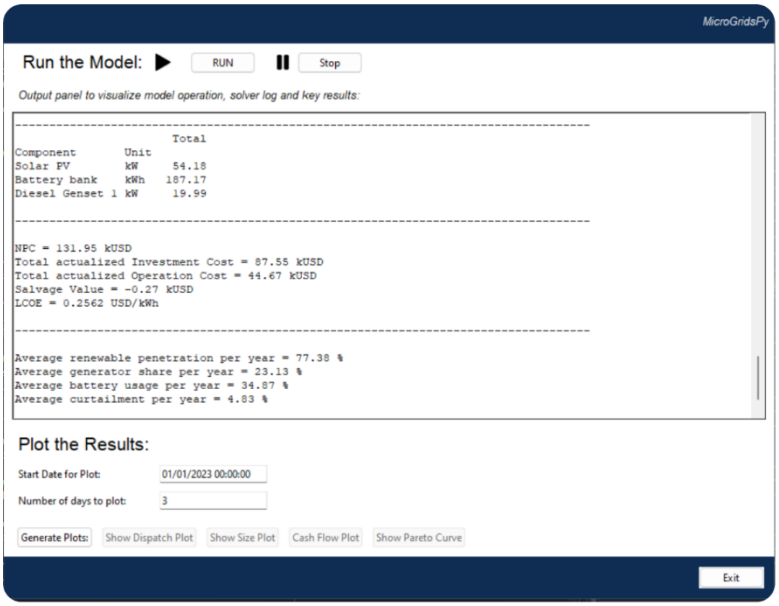
Finally, by pressing the Run but, the MicroGridsPy execution phase will start. A dedicated output panel is included to display the solver's log and system operations as the model runs, offering real-time feedback on the model's computations, including solver operations and key result indicators, as well as errors or issues during the model run.



Upon initiating the model with the 'Run' button, users can **monitor the solver's log** and the **system's operational actions** in **real-time**. This output panel provides a **live feed** of the **model's processing data** displaying also potential errors messages.

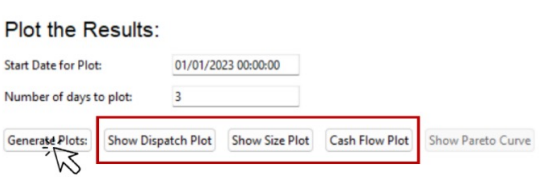
Once the model run is complete, the interface will present key results such as:

- Installed capacities for each RES technology and battery.
- Lifecycle costs including NPC, investment costs, operational costs and LCOE.
- Annual statistics for renewable penetration, battery usage, grid usage and curtailment.

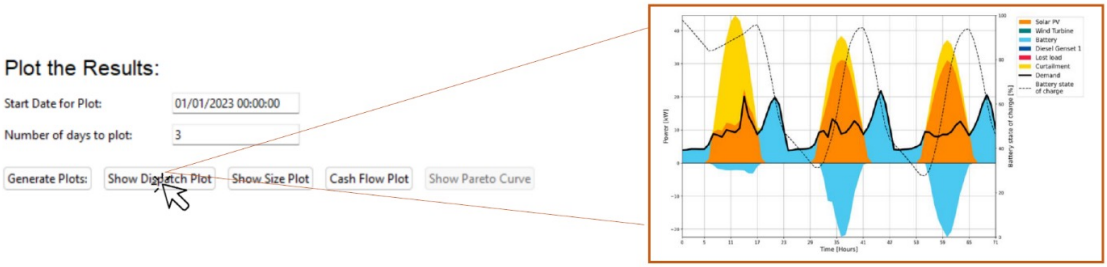


After execution, it displays **key sizing results** such as capacity installed of renewables, backup and storage selected technologies. It provides a **summary of the system's costs**, including the net present cost (NPC), investment costs, operational costs, and the levelized cost of electricity (LCOE). Additionally, it offers **annual statistics** like renewable penetration, generator share, battery usage, and curtailment.

Finally, the GUI offers functionality for plotting model outputs, allowing users to visualize the system's performance over a selected timeframe. By specifying the start date and the number of days to plot, users can generate graphs related to energy dispatch, system sizing, and financial analysis, providing a visual interpretation of the model's operational dynamics and economic viability.



Users can create visual **plots of model outputs** by setting a date range and choosing from various plot types. The buttons **generate graphs for energy dispatch, system sizing and financial analysis**, providing a comprehensive view of the model's performance over the selected timeframe.



8. ANNEX B – SOUTH AFRICAN NATIONAL LAND COVER

The full classification of land cover in the SANLC can be found here: https://egis.environment.gov.za/sa_national_land_cover_datasets. An example is reported in the following table.

No.	Class Name	Class Definition
1	Contiguous Forest (combined very high, high, medium)	Natural tall woody vegetation communities, with 75% or more canopy cover, and canopy heights exceeding 6 metres. Typically representative of tall, indigenous forests. Note that the spatial extent of where spectrally modelled dense woody cover represents indigenous forest is informed by the January 2018 release of the SANBI Vegetation of South Africa dataset (and not the 2006 version as used in the 1990 and 2013–14 SANLC datasets).
2	Contiguous Low Forest & Thicket	Natural tall woody vegetation communities, with 75% or more canopy cover, and canopy heights ranging between 2.5–6 metres. Typically representative of low, indigenous forests and dense thicket communities.
3	Dense Forest & Woodland	Natural tall woody vegetation communities, with canopy cover ranging between 35–75%, and canopy heights exceeding 2.5 metres. Typically represented by dense bush, dense woodland and thicket communities.
4	Open Woodland	Natural tall woody vegetation communities, with canopy cover ranging between 10–35%, and canopy heights exceeding 2.5 metres. Typically represented by open bush and woodland communities.
5	Contiguous & Dense Planted Forest	Dense to contiguous cover, planted tree forests, consisting primarily of exotic timber species, with canopy cover exceeding 35%, and canopy heights exceeding 2.5 metres. Typically represented by mature commercial plantation tree stands. This class also includes smaller woodlots and windbreaks, where they have been identified by the same spectral-based image modelling procedures used to detect the plantation forests.
6	Open & Sparse Planted Forest	Open to sparse cover, planted tree forests, consisting primarily of exotic timber species, with canopy cover ranging between 5–35%, and canopy heights exceeding 2.5 metres. Typically represented by young or recently planted commercial plantation tree stands. This class also include smaller woodlots and windbreaks, as per class 5 above.
7	Temporary Unplanted Forest	Temporarily unplanted stands within commercial forest plantations that have recently been harvested, and/or re-planted but the tree saplings are undetectable on the imagery. Note: to a large degree the extent of these 2018 clear-felled plantation areas has been informed and guided by areas classified as plantations with standing trees in the 2013–14 SANLC dataset, but not having any detectable plantation tree cover in SANLC 2018; as long as no other alternate land-cover or land-use class has replaced the plantation forests.
8	Low Shrubland (other regions)	Natural, low woody shrubland communities, where the total plant canopy cover is typically both dominant over any adjacent bare ground exposure, and the canopy height ranges between 0.2–2 metres. Note: this definition differs slightly from the equivalent gazetted class definition (i.e. total plant canopy cover ranges between 10–100%) in order to provide a more comparable content to the 1990 and 2013–14 SANLC datasets. If a tree or tall bush woody cover is evident it is typically $< 0.1\%$ of total canopy cover. Typically representative of low, indigenous karoo-type vegetation communities, which have been identified using image-based spectral models, but which fall spatially outside the SANBI defined boundaries for Fynbos, Succulent and Nama-Karoo vegetation communities. This is the same approach as used in the 1990 and 2013–14 SANLC datasets, and has been replicated for consistency and comparability.
9	Low Shrubland (Fynbos)	This is the same as class 8, Low Shrubland, but now represents low, indigenous karoo-type vegetation communities, which have been identified using image-based spectral models, but which fall spatially inside the SANBI defined boundaries for Fynbos vegetation communities. This is the same approach as used in the 1990 and 2013–14 SANLC datasets, and has been replicated for consistency and comparability.
10	Low Shrubland (Succulent Karoo)	This is the same as class 8, Low Shrubland, but now represents low, indigenous karoo-type vegetation communities, which have been identified using image-based spectral models, but which fall spatially inside the SANBI defined boundaries for Succulent Karoo vegetation communities.
11	Low Shrubland (Nama Karoo)	This is the same as class 8, Low Shrubland, but now represents low, indigenous karoo-type vegetation communities, which have been identified using image-based spectral models, but which fall spatially inside the SANBI defined boundaries for Nama Karoo vegetation communities.
12	Sparsely Wooded Grassland	Natural woody vegetation, with a woody canopy cover ranging between only 5–10%, and canopy heights exceeding 2.5 metres, in a grass-dominated environment. Typically represented by very sparse woodland or lightly wooded grassland communities. This class has been included as it is part of the new gazetted land-cover classification standards, but is challenging to map with 20 m resolution imagery, since the associated woody cover component is not a spatially dominant component. Whilst the class has been generated with all possible due care and attention, it must be used and with caution, and should be interpreted as a sub-component of the grassland areas, especially in drier more arid areas.

9. ANNEX C – COMMERCIAL REFERENCES FOR PV, BESS AND INVERTER COST ESTIMATION

Table 37: Commercial PV modules

PV component[20]	Cost [R]	Capacity [W]	Specific Cost [R/W]
Jinko Solar Panel Tiger N-Type 440W NEO	1 425.00	440.00	3.24
Jinko Solar Panel Tiger 555W Mono-Facial	1 590.00	555.00	2.86
Jinko Solar Panel Tiger 560W Mono-Facial	1 645.00	560.00	2.94
Jinko Solar Panel NEO N-Type 575W Mono-Facial	1 750.00	575.00	3.04
Jinko Solar Panel NEO N-Type 620W Mono-Facial	3 690.00	620.00	5.95
JA Solar 500W Mono	1 810.00	500.00	3.62
500W SOLARFIRST JA SOLAR PANEL	2 279.00	500.00	4.56
Canadian Slolar 500W	1 999.00	500.00	4.00
Canadian Solar 600W Mono Solar Panel	2 550.00	600.00	4.25
Canadian Solar 460W	1 900.00	460.00	4.13
Average	**2 063.80**	**531.00**	**3.86**

Table 38: Commercial BESS

Battery component[21]	Cost [R]	Capacity [kWh]	Single component specific cost [R/Wh]
Deye Battery 10.6kWh RW-F10.6	34 500.00	10.60	3.25
Dyness 5.12KW Lithium Battery BX51100	15 500.00	5.12	3.03
SUNSYNK 5.1KWH IP65 BATTERY LFP WALL MOUNT 5.1KWH 51.2V	20 590.00	5.10	4.04
PYLONTECH UP5000 4.8KWH LI-ION SOLAR BATTERY 48V	22 850.00	4.80	4.76
Average	**23 360.00**	**6.41**	**3.77**

[20] *References:*

- *Solar Panels – Solar & Inverter Warehouse (inverter-warehouse.co.za)*
- *500W solar panels - Search Shopping (bing.com)*
- *Canadian solar - Search Shopping (bing.com)*
- *Jinko Solar Panel Tiger N-Type 440W NEO*
- *Jinko Solar Panel Tiger 555W Mono-Facial*
- *Jinko Solar Panel Tiger 560W Mono-Facial*
- *Jinko Solar Panel NEO N-Type 575W Mono-Facial*
- *Jinko Solar Panel NEO N-Type 620W Mono-Facial*

[21] *References:*

- *Rechargeable Batteries - Dyness 48V 100Ah 4.8KWH Lifepo4 Lithium Battery A48100 for sale in Johannesburg (ID:620944606) (bobshop.co.za)*
- *https://www.inverter-warehouse.co.za/collections/batteries*
- *Deye Battery 10.6kWh RW-F10.6 – Solar & Inverter Warehouse (inverter-warehouse.co.za)*
- *Dyness 5.12KW Lithium Battery BX51100 – Solar & Inverter Warehouse (inverter-warehouse.co.za)*
- *Sunsynk Battery LFP Wall Mount 5.1kWh 51.2V IP65 (solar-shop.co.za)*
- *Pylontech UP5000 4.8kWh Li-Ion Solar Battery 48V (solar-shop.co.za)*

Table 39: Commercial PV-BESS kits

System	Reference
8Kw Sunsynk Hybrid Dyness Solar Kit	8kw Sunsynk Hybrid Dyness Solar Kit - JC Solar Panels
8kw Sunsynk Hybrid Greenrich 10kwh Solar Kit	8kw Sunsynk Hybrid Greenrich 10kwh Solar Kit - JC Solar Panels
5kw Sunsynk 5.3kwh Solar Kit	5kw Sunsynk 5.3kwh Solar Kit - JC Solar Panels

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Table 40: PV-BESS cost allocation

Component	Total Price PV [R] (Incl. VAT)	Total Price BESS [R] (Incl. VAT)	% price PV	% price BESS
8kw Sunsynk Hybrid Inverter	29899.00	-	31.692%	-
Canadian Solar 555W Mono PERC HiKu6 Solar Panel	32257.44	-	34.192%	-
Dyness 5.12kWh Lithium-ion Battery	-	36479.82	-	69.910%
Permopower Battery Cable 50mm² RED (160A)	-	586.50	-	1.124%
Permopower Battery Cable 50mm² BLACK (160A)	-	586.50	-	1.124%
50mm Battery Lug with 8mm hole	-	207.04	-	0.397%
Permopower Battery Cable 35mm² Black (125A)	-	132.25	-	0.253%
Permopower Battery Cable 35mm² Red (125A)	-	132.25	-	0.253%
35mm Battery Lug with 8mm hole	-	86.00	-	0.165%
AC Protection Box Single-Phase	3333.85	-	3.534%	-
800V 1ka Battery Busbar	-	2183.85	-	4.185%
PV Combiner box 2-in 2-out 1000V 32A	2999.00	-	3.179%	-
100m 6mm Helukabel solar cable Red and Black	4140.00	-	4.388%	-
MC4 Connector Male and Female Pair pack of 5	644.00	-	0.683%	-
Uranus Tile roof 2kw mounting pack	2127.50	-	2.255%	-
Uranus 4.7m rail	4427.50	-	4.693%	-
Trailing Cable 10.0mm x 4 Core	2501.25	-	2.651%	-
Earth Spike M12 x 1.2m threaded	225.40	-	0.239%	-
8kw Standard solar Installation	11786.93	11786.93	12.494%	22.588%
TOT	**94341.87**	**52181.14**	**100%**	**100%**


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