D4.2 – Microgrid design

Deliverable 4.2 – Microgrid design

TwInSolar

(Improving Research and Innovation to achieve a massive integration of Solar renewables)

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Contents

Executive summary

This deliverable introduces ERMESS an algorithmic optimization and decision-support tool aiming at finding the optimal design of electric microgrids. Originally developed for the design of the Terre Sainte microgrid, in Saint-Pierre on La Reunion, ERMESS enables the optimal sizing and configuration of energy systems within a microgrid, based on user-defined objectives and constraints. Specifically, it identifies the most suitable combination of generation technologies, energy storage types and capacities, and proposes appropriate energy management and demand response strategies.

This deliverable presents the algorithmic framework underlying ERMESS, including its optimization methodology, implementation features, and key assumptions. It also outlines the tool's intended usage, potential applications, and the type of insights it can generate for planners and decision-makers. Finally, we present the campus of Terre Sainte and we apply ERMESS to this real-world case-study to illustrate its capabilities. Then, these results constitute a proposal for the actual design of the future microgrid.

I. General points about microgrids

A) Objectives

Microgrids are established either from technical necessity – as it is the case for many non-interconnected islands territories - or through the initiative of local stakeholders aiming to enhance energy self-sufficiency, economic performance, or environmental sustainability.

From a technical standpoint, leveraging locally available resources increases grid autonomy by reducing reliance on energy imports and minimizing transmission losses. Local energy production and management encourage user engagement, generate employment opportunities, strengthen cooperation among local stakeholders, and raise awareness of consumption behaviors and the value of demand-side flexibility. Furthermore, microgrids serve as effective educational and research platforms, supporting innovation and the development of new technologies.

Their typical scale makes microgrids particularly suitable for the integration of renewable energy sources, thereby contributing to reduced environmental impacts. Widespread deployment of microgrids also support efforts to reduce dependence on fossil fuels and mitigate greenhouse gas emissions.

Economically, transitioning to a microgrid transforms the cost structure faced by users. Instead of high costs associated to large-scale energy production, long-distance transmission, and importation, users face costs primarily linked to equipment procurement, system management and local energy balancing. While the economic viability should be assessed on a case-by-case basis, microgrids are generally very competitive over the long term.

B) Energy production

Achieving a high level of electrical autonomy requires sufficient local generation capacity to meet the energy demand of the microgrid. This depends on the careful selection of generation technologies based on the availability of local energy resources. The level of production must be aligned with the autonomy targets set by the operators.

Controllable (or “dispatchable”) energy sources offer the advantage of dynamically adjusting their output to match fluctuations in electricity demand. At the microgrid scale, such sources may include hydroelectric, geothermal, or biomass-based generation. Diesel generators—typically powered by heavy fuels—are also used due to their high operational flexibility, although they remain highly polluting and significant emitters of greenhouse gases.

In contrast, variable energy sources—such as wind turbines, photovoltaic systems, and run-of-river hydropower plants (which lack upstream water storage capacity)— introduce operational challenges due to their intermittency, variability and unpredictability. Nevertheless, these sources are characterized by minimal environmental impact and currently benefit from favorable regulatory frameworks that encourage their deployment.

C) Microgrid balancing

The stability of any power grid requires balancing between power injection and withdrawal at all times. The process of simultaneously managing energy generation, distribution, and consumption to ensure this balance is known as grid balancing. While isolated microgrids must manage this balance locally, interconnected microgrids can rely on energy imports or exports. However, doing so negatively affects the system's self-sufficiency.

Balancing is relatively straightforward when the microgrid is significantly powered by controllable sources. It becomes increasingly complex as the share of variable and intermittent sources grows. The variability of these sources can cause mismatches between supply and demand, requiring sophisticated strategies to maintain grid balance. Flexibility mechanisms refer to any technique that helps maintain this equilibrium. These mechanisms can take various forms: energy storage systems, implicit or explicit demand-side management, etc.

To mitigate the effects of renewable intermittency and variability, the scientific literature recommends maximizing the diversity of energy sources to exploit their temporal complementarities. Ideally, the combined production dynamics of these sources should closely match the consumption patterns of the site.

For example, a microgrid with high nighttime consumption should limit its reliance on solar energy, whose output is inherently zero at night, and instead prioritize other sources (potentially in combination with solar). If this is not feasible, increasing self-sufficiency necessarily requires the integration of flexibility solutions.

D) Flexibility options

There are two principal strategies for achieving temporal alignment between electricity consumption and production in a microgrid.

The first treats consumption as a fixed constraint and seeks to adjust production accordingly. This can be achieved by integrating controllable generation assets or energy storage systems capable of mitigating production variability. Storage technologies can absorb excess electricity when supply exceeds demand and can release it when the opposite occurs. Storage systems are characterized by the services they provide to the grid. Some, such as flywheels and supercapacitors, provide high power output over short durations; others, like thermal storage, hydrogen systems, or compressed air energy storage ("CAES"), can store large quantities of energy but are less suited to fast response. Electrochemical batteries offer a balanced compromise in terms of power and energy capacity. Each storage technology plays a specific role in microgrid operation, and the optimal configuration often involves a well-balanced combination of multiple storage solutions.

The second approach involves direct actions on consumption. Two complementary objectives should be pursued: reducing overall demand through energy-saving measures (e.g., energy-efficient equipment, user awareness campaigns, and incentives for energy sobriety) and managing residual demand to align with available production using demand-side management tools. Smart meters allow precise measurement of consumption and support dynamic pricing schemes while enabling active load control, so they can become a key component of demand-side management.

Naturally, it is possible—and often beneficial—to combine both approaches, managing consumption, storage, and controllable production sources simultaneously. Thus, microgrid design must address decisions regarding energy storage systems and demand-side management, which involve complex trade-offs between cost, sustainability, performance, and safety:

- Which production technologies should be prioritized?
- What flexibility solutions should be implemented?
- Which overall management strategy should be adopted?
- How should different technologies be sized and coordinated?
- Under what conditions should energy be stored, discharged, imported, or exported?
- What are the associated capital and operational costs, and is the project economically viable?
- What level of energy autonomy is realistically achievable?
- What are the environmental, economic, and societal impacts of the microgrid?

Providing rigorous, quantitative answers to these questions is inherently challenging. To support this process, the PIMENT laboratory has developed ERMESS ("EvolutionnaRy Microgrid Energy Systems Sizing"), an advanced software tool designed to optimize microgrid design under multiple technical and economic criteria.

II. ERMESS and microgrid modelling

A) General hypotheses and constraints

ERMESS models a microgrid as a set of interconnected physical and electrical components, each contributing to the system's overall performance. The main elements of the model include:

1. A set of electricity production devices, such as photovoltaic panels, wind turbines or dispatchable power sources like diesel generator.
2. A set of energy storage systems, characterized by their maximal power and energy capacity.
3. A power management system (PMS) which follows a real-time strategy of dispatching. It defines the power flows between the different components and with any connected external grids. It also governs demand-side management if there are deferrable loads.
4. A contract specification with connected external grids (if any) which specify the conditions and prices of power import/export.

The core objective of ERMESS is to identify the optimal combination of components that satisfies a user-defined constrained optimization problem. The constraint typically refers to a minimum level of self-sufficiency or self-consumption, while the performance indicator to be optimized can be one parameter (or a combination of parameters) chosen among the following set of techno-economic and environmental performance indicators:

- Levelized cost of the demand (“LCOD”),
- Annual net benefits,
- Net present value (“NPV”),
- Self-sufficiency,
- Self-consumption,
- Autonomy,
- Greenhouse gas emissions,
- Fossil fuel consumption,
- Energy return on energy invested (“EROI”).

Formally, the algorithm solves a problem represented as:

$$\min_{x \in K_{param}} f_{cost}(x) \text{ subject to } f_{cons}(x) > L_{cons}$$

where f_{cost} is the cost (or objective) function (e.g. cost or emissions), x is the vector of decision variables (containing the component parameters), K_{param} is the feasible parameter space, f_{cons} is the constraint function (e.g. self-sufficiency or self-consumption) and L_{cons} is the user-defined constraint level.

ERMESS is designed for flexibility: it supports multiple objective and constraint functions, and the evolutionary algorithm employed does not require convexity or continuity of the cost function. This makes it well-suited for real-world, non-linear energy system optimization. Defining a new cost or constraint function can be done with minimal effort: defining a new cost function is fastened by the versatility of evolutionary algorithms.

Only electrical energy flows are considered in the model. Thermal or fluidic exchanges are excluded. The entire microgrid is assumed to operate under alternating current (AC), except for DC sources like PV arrays, which are converted via inverters. No transmission losses are assumed between components (given the short cable lengths in typical microgrids), but device-level losses (e.g., in storage and generation units) are fully accounted for. Each component is characterized by a time series of power values over the simulation horizon. Power balance at every time step is maintained using the following conservation of energy equation:

$$\forall t \in [0, t_f], 0 \leq p_{clipping}(t) = p_{prod}(t) + p_{storage}(t) + p_{connexions}(t) - p_{load}(t)$$

We introduce here $p_{clipping}$, the surplus power that cannot be consumed in-situ, stored, or exported. In most cases, $p_{clipping} = 0$, but when the load is already supplied, the storage full and the grid cut-off, we can observe $p_{clipping} > 0$; and the excess power is diverted to a resistive load (e.g. a boiler). This term is strictly non-negative: when demand exceeds available supply, and no corrective action (e.g., load shedding) is taken, system instability occurs—voltage and frequency drop, followed by generator shutdown and potential blackout.

B) Components definitions and modelling

Electrical consumption

ERMESS model divides electricity demand into three components, based on their degree of flexibility :

- Non-deferrable load: A fixed time series representing critical loads that must be met and cannot be altered during the optimization process.
- Daily deferrable load: An energy demand that must be satisfied within each day, but whose exact timing within the day is flexible. This time series is subject to optimization.
- Yearly deferrable load: An energy demand that must be fulfilled over the course of the year, with complete temporal flexibility. This component is also subject to optimization.

The total site load is the sum of these three time series. From a modeling standpoint, the load is both a constraint (non-deferrable consumption) and an optimization variable, since the scheduling of deferrable loads can be adjusted to better align with generation and storage availability.

Renewable energy production

ERMESS supports two approaches for defining on-site renewable generation profiles. Manually, the user may directly provide time series representing the power output of specific renewable energy devices over the optimization horizon. Alternatively, ERMESS can generate production profiles using external libraries (pvlib for PV systems and WindPowerlib for wind turbines). In this case, the user must supply technical specifications of devices, geographic parameters (e.g. orientation, tilt, hub height) and site-specific meteorological data.

Whatever the chosen approach, a renewable production dataset consists of a list of installable renewable devices, each characterized by production profile and technical and economic parameters (e.g., installation and maintenance costs, energy yield, spatial constraints, etc.). It is transferred to the optimization process as an input data. At the end of the optimization process, ERMESS outputs the recommended installed capacity for each technology, enabling the user to identify the optimal sizing and composition of the renewable energy portfolio.

Storage devices

Storage devices are modelled in a simple manner to enable the comparison of various storage technologies. Currently, the following options are considered:

- electrochemical batteries (e.g. lithium-Ion, lead-acid, nickel-cadmium),

- compressed Air Energy Storage (CAES),
- flywheels,
- pumped-storage hydroelectricity,
- hydrogen-based systems,
- and supercapacitors.

Users also have the option to manually define a custom storage system by specifying its technical, environmental and economic characteristics. Hereafter are the main parameters which characterize a storage system in ERMESS:

- Depth of charge: Certain technologies are sensitive to operating outside specified state-of-charge (SOC) limits, which can cause rapid degradation,
- Round-trip efficiency factor: The ratio of energy retrieved to energy stored,
- Lifetime: Expressed in both calendar years and charge/discharge cycles,
- Cost components: These include installation cost, energy cost (proportional to storage capacity), power cost (proportional to power rating), and operation and maintenance costs,
- Environmental impact: Assessed in terms of greenhouse gas emissions over the device's lifetime,
- ESOEI (Energy stored on energy invested),
- Storage capacity,
- Maximum input and output power.

While storage capacity and maximum input/output powers are optimization variables, all the other parameters are treated as constraints and must be provided by the user. Since costs vary depending on the technology, ERMESS evaluates all available storage options and determines the optimal configuration. It selects or excludes each technology based on its utility and its contribution to the microgrid's overall performance.

Dispatchable power sources

A dispatchable power source, typically a diesel generator in the context of microgrids, is characterized in ERMESS PRO by the following parameters:

- Minimum, rated and maximum output power,
- Fuel consumption curve, modeled as an affine (linear with offset) function of output power,
- Fuel price,
- Cost components: including installation cost, power cost, and operation and maintenance cost,
- Environmental impact: quantified by lifetime greenhouse gas emissions,
- Lifetime: expressed in operational hours.

Grid connection

ERMESS handles grid connection and electricity trading. Trading conditions are governed by a contract specifying time-dependent buying and selling price schedules, as well as an availability schedule to account for unreliable grid connections.

When multiple contracts are available for a given connection, ERMESS PRO automatically selects the most advantageous option based on the system's operational performance.

Dispatching strategy

The diversity of devices integrated into a microgrid requires the optimization of electrical power flow. This task is handled by a dispatching strategy, typically implemented in real time by a Power Management System (PMS). The strategy involves decisions related to power allocation, deferrable load management, and the control of dispatchable power sources.

The dispatching strategy in ERMESS is defined by the following parameters:

- Dispatchable management strategy: Selected from a predefined set of strategies, it defines operational constraints such as the minimum runtime and minimum production level for dispatchable power sources.
- Discharge order: Determines the sequence in which storage systems are discharged.
- Taking over parameter: Specifies the extent to which a secondary storage system is used when the state of charge (SOC) of a primary system approaches its upper or lower critical limits.
- DSM minimum levels: Define thresholds for managing deferrable loads within the microgrid.
- Repartition coefficient: Controls how excess power is distributed between deferrable loads and storage.

As such, ERMESS PRO implements a deterministic, data-driven dispatching strategy, selected from a set of predefined rules to ensure efficient and reliable microgrid operation.

Summary

The following Sankey diagram shows the various inputs (user-defined constraints) and outputs (optimization variables) that ERMESS manages and/or generates.

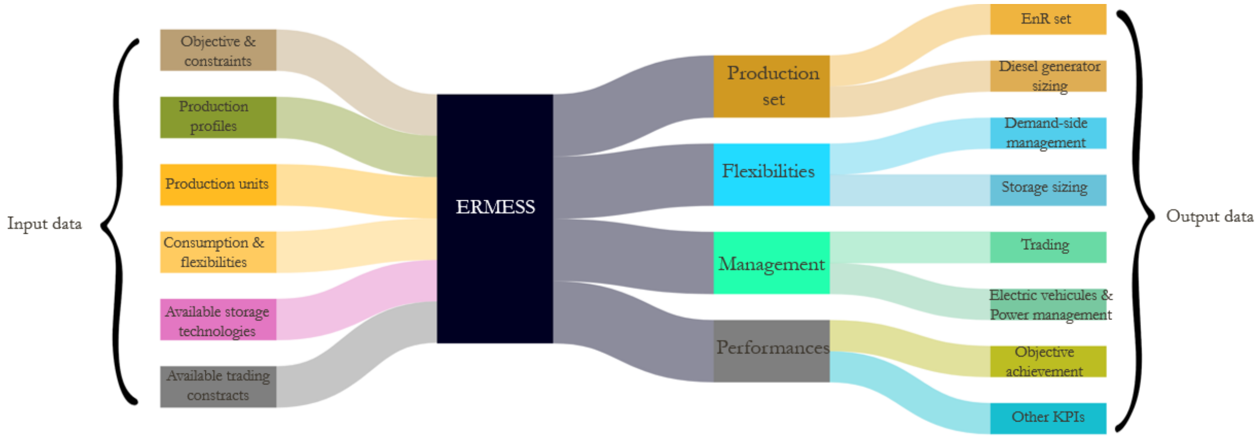

Figure 1 : Input-process-output diagram of ERMESS

C) Resolution method

Sizing an entire microgrid involves addressing a highly complex optimization problem composed of diverse subproblems, each corresponding to a specific device with its own behavior and constraints. Furthermore, the variety of cost functions used requires a solving method that is flexible, adaptative and robust.

Although the system constraints are often linear—yielding a solution space that is a polyhedron—traditional optimization techniques such as linear or quadratic programming are inadequate when the objective functions are non-convex or involve non-linear forms such as rational functions. Evolutionary algorithms have proven to be a powerful and suitable approach for solving this type of problem and is the basis of the core of ERMESS optimization process.

An evolutionary optimization algorithm mimics natural selection processes to explore the solution space and converge toward an optimal configuration. It operates on a *population* of candidate solutions, where each member (or *individual*) represents a potential solution (here a microgrid configuration). Each individual's genotype consists of:

- A set of renewable power production devices,
- A set of sized storage devices,
- A set of dispatchable power sources,
- A set of grid connection contracts (if applicable),
- A dispatching strategy.

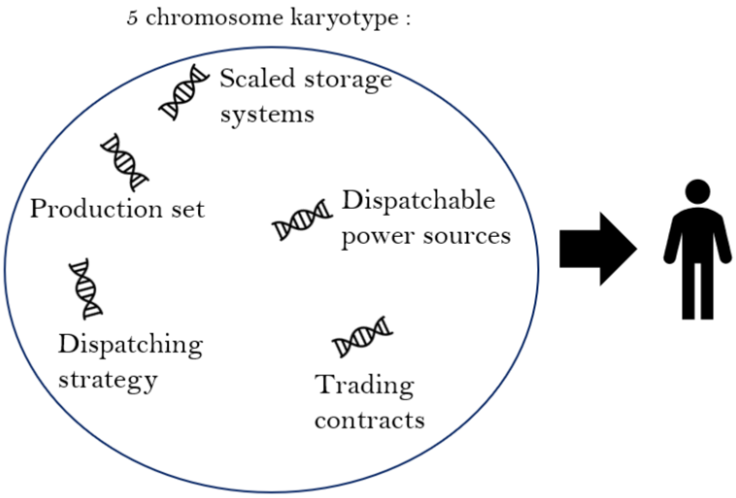

Figure 2 : Genotype of an individual in ERMESS

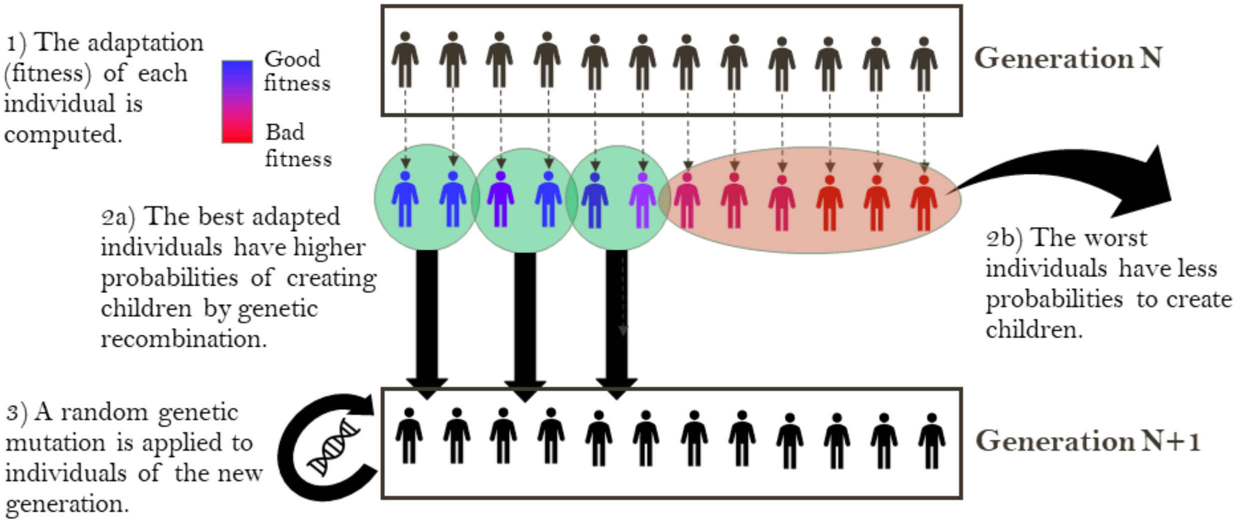

Figure 3 : Simplified representation of simulated processes in evolutionary algorithms

The population evolves over successive generations through algorithmic routines which mimic the processes of selection, mutation and reproduction. These evolutionary operations allow the algorithm to iteratively improve the quality of the solutions. Several hyperparameters govern the behavior of the algorithm and can be tuned by the user, including population size, stopping criterion, crossover probability and mutation rate. Previous studies on evolutionary algorithms have demonstrated their ability to generate increasingly high-performing individuals over time. As generations progress, the algorithm tends to converge toward more optimal solutions.

III. Designing the microgrid of Terre Sainte using ERMESS

A) The case of the campus of Terre Sainte

The university campus of Terre Sainte, in Saint-Pierre of La Reunion, includes the ESIROI, the only French engineering school in the Indian Ocean, the SEAS-OI, a facility dedicated to satellite-based environmental monitoring, the university institute of technology of Saint-Pierre, a university restaurant and a student residence complex (see Figure 4 for overview). The goal of the TwInSolar project is to design a microgrid for this campus capable of ensuring an 80% level of self-sufficiency rate in electric consumption.

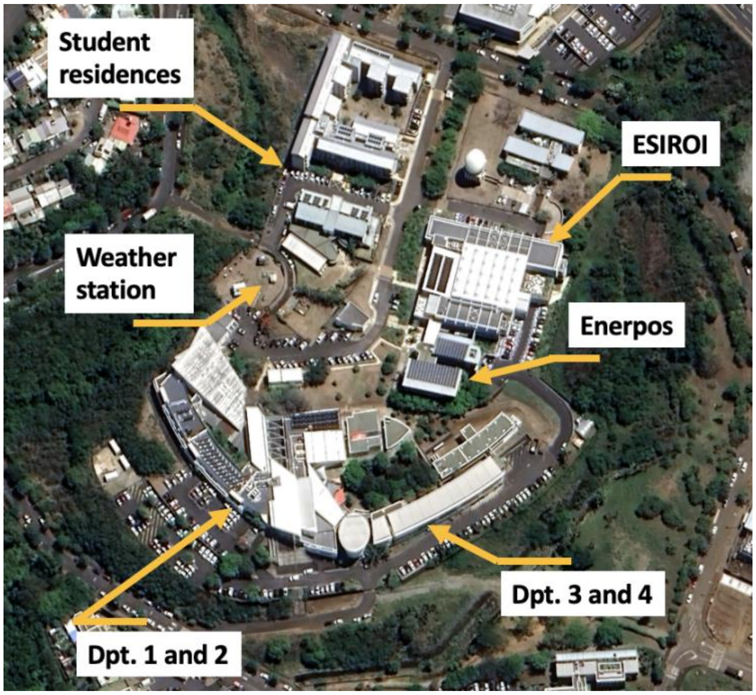

Figure 4 : The university campus of Terre Sainte, Saint-Pierre, La Reunion

The annual average electric consumption reaches 1337 MWh/year, and is currently mainly supplied by the main grid at an average cost of 0.22 €/kWh. More than half of this energy is dedicated to cooling purposes (air conditioning, ventilation systems and cold rooms), resulting in a significant seasonal variability. During summer, peak power demand can be twice as high as in winter. In addition, daily and weekly variabilities further complicate the management of the local energy system.

Photovoltaic systems are already operational on site, producing approximately 267 MWh/year, which covers about 20% of the electricity needs. However, this production level is insufficient regarding the self-sufficiency target, and the addition of new production assets is therefore essential.

Although several studies suggest to use complementarity between different energy sources to enhance microgrid reliability, the spatial constraints of the campus prevent the installation of ground-mounted systems. Only rooftop-integrated technologies, which can be solar modules or rooftop wind turbines, can be considered. The maximal installable PV capacity is 845 kWp: it corresponds to the scenario where all suitable roof surfaces are entirely covered. A preliminary study has shown that increasing PV capacity alone, without integrating flexibility mechanisms (deferrable load or storage systems) does not lead to high self-sufficiency levels (see Figure 5).

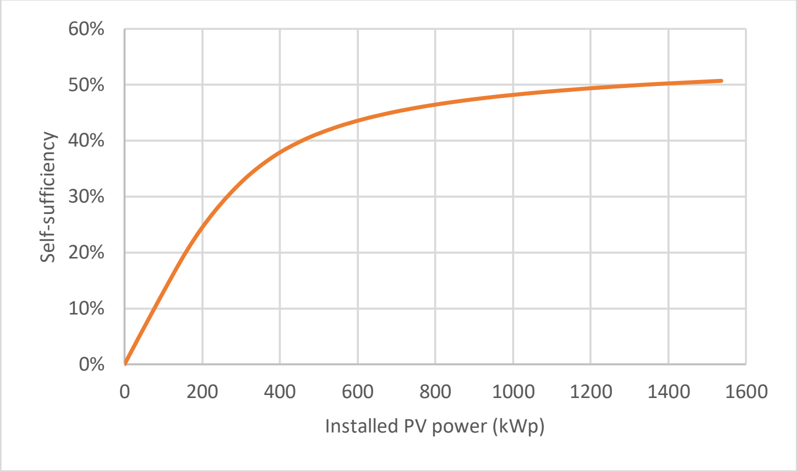

Figure 5 : Evolution of the self-sufficiency of the campus without storage.

These preliminary results demonstrate why ambitious self-sufficiency targets cannot be achieved with simple system designs. They justify the need for a comprehensive optimization tool such as ERMESS, capable of determining both the optimal sizing of components and their optimal management and interactions within the microgrid.

The installation and maintenance costs of additional production and storage systems have been estimated, with significant variation depending on roof type (sheet metal, terrace, flat roof, etc.)

A preliminary study (LE GAL LA SALLE, 2023) conducted without ERMESS but using state-of-the-art sizing methodologies, provided a first estimate of the required system components to meet the energy goals. The proposed configuration included 588 kWp of additional photovoltaic modules, a short-term storage system (typically an electrochemical battery) of 1.6 MWh of energy and 600 kW of power, a long-term storage system (typically hydrogen or CAES) of 3 MWh. It also needs a user sensibilization program resulting in a reduction of 5 MWh/year in electricity demand.

B) A competitive design with ERMESS

Inputs

An optimization has been conducted with ERMESS, using the following parameters. The objective function is the cost of delivered electricity (LCOD), with the constraint that self-sufficiency should be 80% minimum. The consumption has been assumed to be fully non-deferrable. This choice could be discussed, as numerous loads can be considered easily deferrable in reality (electric vehicle, domestic hot water, etc.)

The geographic characteristics (tilt, orientation, material) of the 23 available rooftops have been used to simulate the production obtained with 400 Wp solar modules. ERMESS was constrained to use only lithium-ion electrochemical batteries with a round-trip efficiency of 80%. The campus remained connected to the main power grid of La Reunion; however, exporting electricity to the grid was not permitted.

Outputs

ERMESS identified a solution that achieves a competitive LCOD (0.255 €/kWh) while satisfying the 80% self-sufficiency constraint. This solution includes the installation of 692 kWp of new photovoltaic capacity. Figure 6 shows the recommended PV coverage ratio for each available rooftop in the campus, ranging from 0% (no PV installation recommended) to 100% (full rooftop coverage). To meet the 80% self-sufficiency target, most coverage ratios are close to 100%. The annual on-site energy production reaches 1.37 GWh/year.

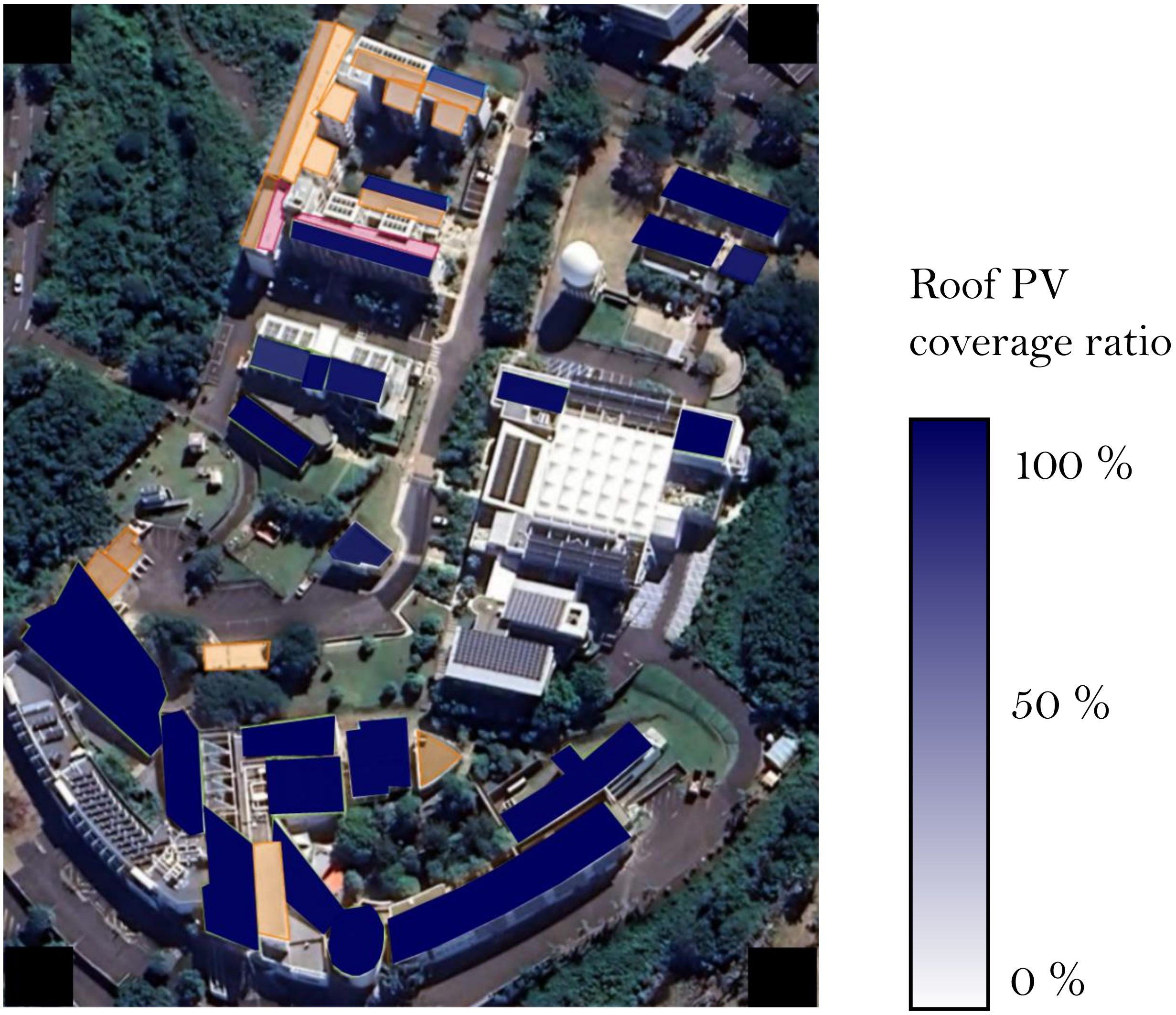

Figure 6 : Map of the PV coverage ratio of each map of the campus to reach a self-sufficiency of 80%

Since load deferral was not permitted, ERMESS recommends the installation of a lithium-ion battery of 3.18 MWh (capable of delivering a power of 305 kW), to better align production with consumption profiles. Under this configuration, 681 MWh/year are stored in the battery, and 136 MWh/year are lost during charging/discharging cycles due to round-trip inefficiencies. 267 MWh are imported from the main grid to meet residual demand. Figure 7 illustrates how the energy is dispatched on a representative day. Note that negative values indicate power drawn from the microgrid, whereas positive values represent power injected into the microgrid. Not surprisingly, the primary role of the battery is to shift excess solar energy produced at midday to cover morning, evening, and nighttime demand.

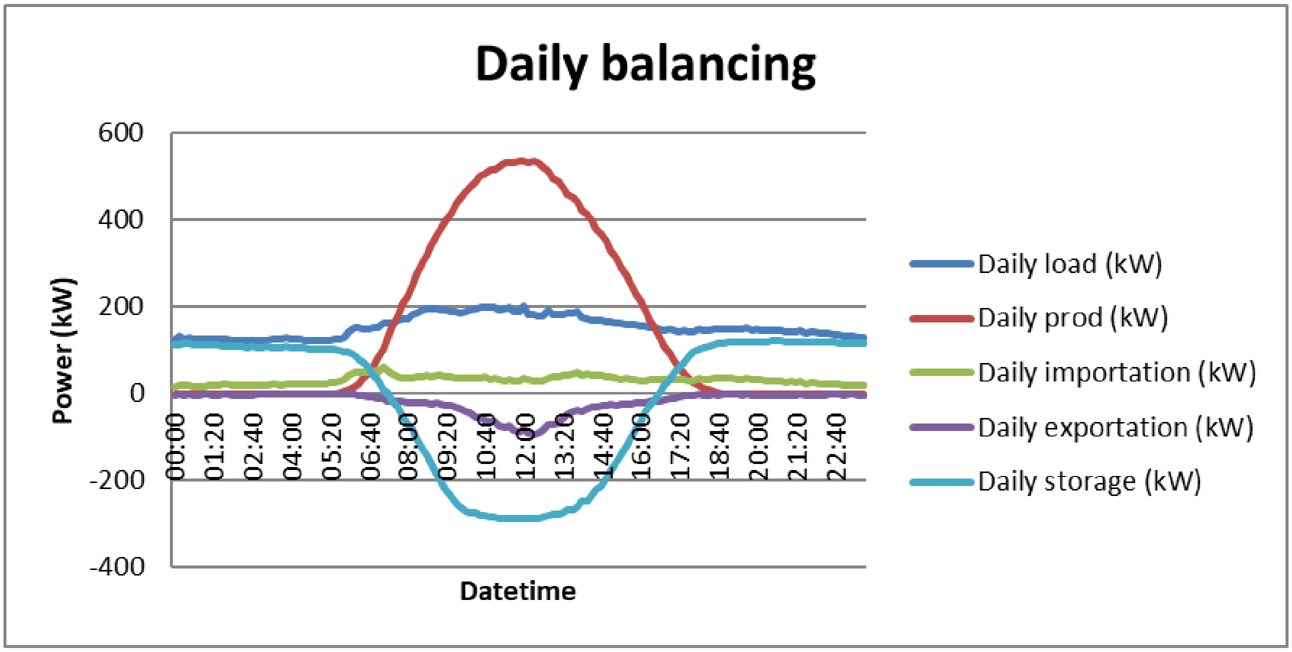

Figure 7 : Energy balancing for the solution proposed by ERMESS (values averaged over all days of the optimization)

The installation of additional solar PV capacity and a storage system significantly decreases the cost of energy importation, but introduces new expense items: OPEX storage, CAPEX storage, OPEX production and CAPEX production. Figure 8 presents a detailed cost breakdown of the proposed solution. If the solution recommended by ERMESS is implemented, the installation of the lithium-ion storage system ("CAPEX Li-Ion") becomes the largest cost component of the project.

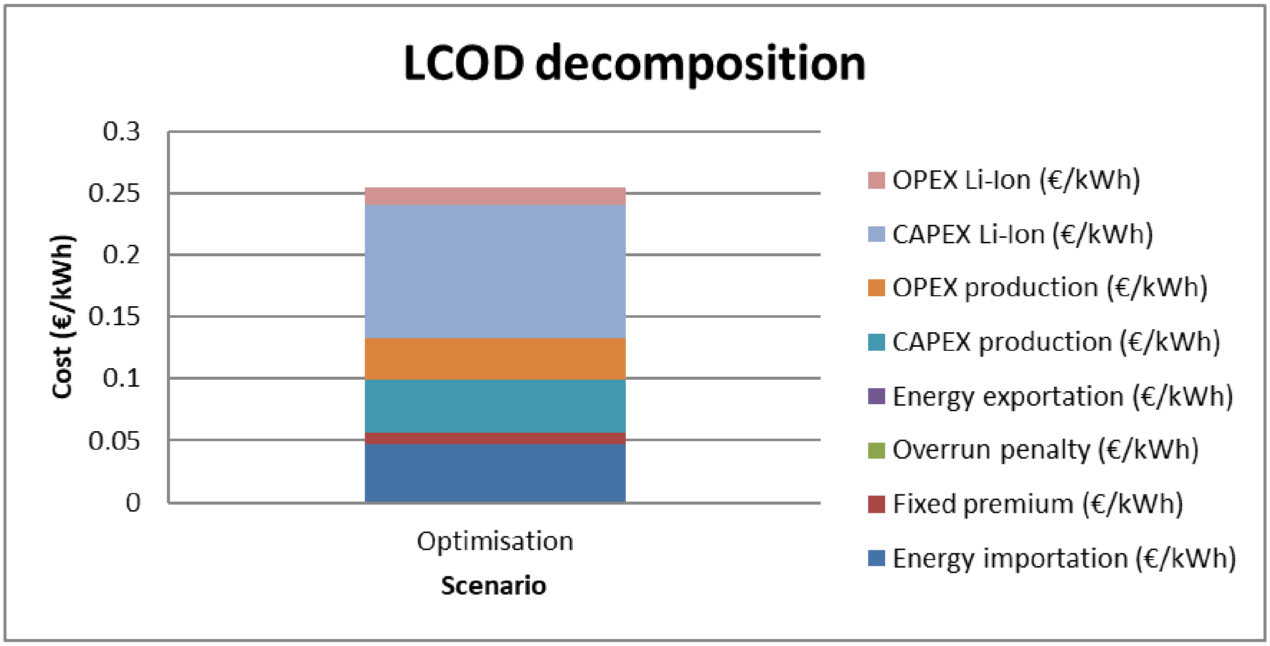

Figure 8 : Decomposition of the LCOD of the solution proposed by ERMESS

Conclusion

In order to find the optimal design for a microgrid at the university campus of Terre Sainte, the laboratory PIMENT developed an innovative optimization tool called ERMESS. This user-friendly platform leverages evolutionary algorithm to determine the best configuration of energy systems based on user-defined performance criteria.

ERMESS was successfully applied to the case of Terre Sainte, delivering a configuration that achieves 80% self-sufficiency while maintaining a competitive Levelized Cost of Delivered electricity (LCOD). Given its flexibility and robustness, ERMESS is expected to be a valuable decision-support tool for other microgrid projects.

Bibliographie

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