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Abstract

The design of off-grid electrification projects considering hybrid systems and distribution microgrids is a complex task that requires the use of decision support tools. Most of existing tools focus on the design of hybrid systems without defining generator locations and microgrids configuration. Recently a deterministic heuristic was developed to solve the problem. In this study we present an enhanced deterministic heuristic and then a meta-heuristic procedure for designing community off-grid electrification projects based on renewable energies considering micro-scale resource variations and a combination of independent generation points and microgrids. Both new algorithms improve performance of the previous existing procedure. The new deterministic heuristic can rapidly (in a computational time lower than 1 minute) obtain a good solution. On the other hand, the proposed meta-heuristic method considerably enhances solutions obtained by the deterministic heuristic with a computational time of 1 hour on a standard PC. The improvement tends to raise as the complexity of the analyzed instance increases. The proposed algorithm is a complete design tool that can efficiently support the design of stand-alone community electrification projects requiring of low computational resources.

Nomenclature

- *A*(*m*): Set of arches of microgrid *m*
- *AVEREMS*: Autonomous Village Electrification through Renewable Energy and Microgrid Systems
- *DP*(*m*): Set of demand points of microgrid *m*
- *GGS*: Grid Generation Score
- *GRASP*: Greedy Randomized Adaptive Search Procedure
- *IGS*: Independent Generation Score
- *L*(*x*,*y*): Euclidean distance between point *x* and *y*
- *LA*(*a*): Length of arch *a*
- *MS*(*s*): Set of microgrids of solution *s*
- *NGS*: No-generation Score
- *P*(*m*): Set of points of microgrid *m*
- *PD*(*u*): Electrical power demand of user *u*
- *RCL*: Restricted Candidate List (of the GRASP)
- *R*(*m*): Generation point (root) of microgrid *m*
- *S*(*M*): Solution composed by microgrids of set *M*

1. Introduction

Projects relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously [1]. These systems produce electricity in a clean way, their cost is often lower than national grid extension and they are not dependent from continuous fuel supply (such as diesel generators), therefore increasing projects long-term sustainability [2]. In this context, the configurations that proved to be the most reliable design options are hybrid systems that combine different generation resources [3] and distribution microgrids, where the energy is produced in a certain point and distributed through an electric microgrid to other consumption points [4].

The design of off-grid renewable energy projects considering hybrid systems and distribution microgrids must consider multiple issues. When designing hybrid systems, the most adequate combination of technologies should be evaluated depending on available resources and generation and storage equipments characteristics. When designing microgrids, the selection of grid generation points and the definition of which points should be connected to a certain micro-grid and which not are complex tasks, especially when a resource (e.g. wind) is highly disperse [5] and best areas for installing generators could be located far from demand points [6]. Furthermore, in scattered communities with isolated users, the combination of multiple microgrids and independent generation points is generally the cheapest design solution [7].

Over last decade, many tools have been developed in order to support the design [8]. However, most of them define the best combination of energy resources in one point but without designing the distribution through microgrids and without taking into account resource spatial variations. The only known method that permits the design of off-grid electrification projects based on multiple renewable energies considering micro-scale resource variations, a combination of independent generation points and microgrids and considering generation in every point of an area (not only close to the users) is the deterministic greedy heuristic proposed in [9].

The problem solved is called AVEREMS: the Autonomous Village Electrification through Renewable Energy and Microgrid Systems [9]. The solutions of that algorithm were shown to considerably improve those obtained by other procedures that, with some limitations, deal with the same design problem: VIPOR software [10] and the mathematical model presented in [7]. However, the algorithm proposed by [9] has some possible weaknesses. Firstly, it creates microgrids always minimizing cable length, while in some cases it would be preferable to utilize a different network configuration in order to reduce utilized cable unitary cost and thus microgrid cost. Furthermore, it is a deterministic procedure in which a single solution is greedily constructed and then improved by a local search phase. It should be noted that the solution obtained by the local search, i.e. local optimum, could be far from the global optimum, i.e. the best of all feasible solutions.

In the last few decades, various meta-heuristic procedures have been developed in order to escape from local optima and thus improve solutions encountered by deterministic heuristics [11]. One of those is the GRASP (Greedy Randomized Adaptive Search Procedure) [12] that has been successfully applied to various location optimization problems [13]. In particular, a GRASP based procedure demonstrated to be highly efficient in solving the capacitated plant location problem [14],which has various similarities with the AVEREMS problem (see [9]).

In this study we present an improved deterministic heuristic and then a meta-heuristic procedure, based on the GRASP, for solving the AVEREMS problem; that is, for designing community off-grid electrification projects based on renewable energies considering micro-scale resource variations and a combination of independent generation points and microgrids. The contribution of the paper is to propose an algorithm that obtains better results than currently available procedures with low computational requirements. In this paper the first meta-heuristic algorithm specifically designed for this purpose is proposed while previous methods were based on simpler procedures. The proposed methods consider the design of multiple microgrids and independent users, the use of hybrid systems combining different renewable energies and the installation of generators far from demand points.

The rest of the paper is organized as follows. Section 2 presents the components of a general off-grid electrification project and the basic problem statement of the AVEREMS. An enhancement to the deterministic heuristic method described in [9] is proposed in Section 3. Various versions of the proposed GRASP based algorithm are described in detail in Section 4. In Section 5 the best version is identified and its performance is compared with the existing procedure. Section 6 deals with the conclusions.

2. The AVEREMS problem

In this Section, after defining the main glossary used (sub-Section 2.1), the components of a hybrid off-grid electrification system (sub-Section 2.2) and the AVEREMS problem are described (sub-Section 2.3).

2.1 Glossary

The main terms used to describe the problem and the methods proposed in Sections 3 and 4 are hereby defined:

- Demand point (or user): location of a consumption point, such as a house or a public building, with certain electric energy and power demands. Demand points can be generation points.
- Distribution system: the electric cables that connect the generation system to the users.
- Generation point: location where a generation system is installed.
- Generation system: group of components installed in a certain point in order to generate and store the electricity. It includes generators (wind turbines and solar panels), controllers, batteries and inverters.
- Grid consumption point (or no-generation point): a user connected to a multiple points' microgrid and not being the generation point. It just consumes energy.
- Grid generation point: generation point of a microgrid composed by multiple points
- Independent generation point (or independent generation system): a user that is producing energy just for its own consumption.
- Microgrid: set of one or more users fed by a generation system placed in a demand or no-demand point. It includes both the generation and the distribution systems.
- No-demand point: location (that is not a demand point) that can be a generation point.

2.2 Components of an off-grid electrification system

The scheme of the elements involved in an autonomous electrification system considering wind and solar energies is as follows (Fig. 1):

1) Generators: produce energy in alternating (wind turbines) or direct (solar panels) current.
2) Controllers: convert to direct current and control the charge/discharge of the batteries.
3) Batteries: store the energy produced by the generators, receive and supply electricity at direct current.
4) Inverters: convert direct to alternating current at the nominal voltage.
5) Electric cables: configure the microgrid that distributes the energy (only low voltage distribution is considered).

6) Electric meters: measure the energy consumed at the demand points.
7) Users (or Demand points): consume the energy.

Please insert Figure 1

The generation system is composed by the generators (wind turbines and/or solar panels), controllers, batteries and inverters. The energy produced by a generation system is distributed to the users by electric cables (distribution system). The term "microgrid" in this paper refers to the ensemble of the generation and the distribution systems. A microgrid composed by a single demand point with the generation system located in the same point is also referred to as an "independent generation point". The radial microgrid configuration (i.e. a single generation system per microgrid and distribution in form of a tree as in Fig. 1) is considered in this study as it is the preferred one in rural electrification projects [15].

2.3 Problem statement

The aim of the AVEREMS design problem is to find the lowest cost configuration (generation points' locations and microgrids design) that accomplish with the energy and power demands of all the users, taking into account energy resource maps and different technical constraints. A detailed description of the AVEREMS problem constraints and mathematical formulation is reported in Appendix A. Next, the objective function of the problem and the constraints of the generation and distribution systems (Fig. 1) are resumed:

- Objective function: To minimize the capital cost of the project, considering all components defined in Fig. 1, i.e. wind turbines, wind controllers, solar photo-voltaic (PV) panels, solar controllers, batteries, inverters, meters, and cables.

- Constraints of the *generation system*: In each generation point, generators, controllers, inverters and batteries must be installed in order to cover the energy and power demands of connected users. The demand of the users is estimated at the horizon time of the project to consider the possible load growth. Generators and batteries must satisfy the energy demand, while inverters must fulfill the power demand. For the dimensioning of the generators, batteries and inverters the following aspects must be also considered: energy resources available in the area, energy and power losses due to equipments' efficiencies, the minimum days of autonomy and the maximum battery discharge factor. In particular, the required days of autonomy are set in order to take into account the uncertainty in the wind and solar resource generation (e.g. as higher the uncertainty for a certain project, higher the days of autonomy of the batteries). This feature together with the consideration of the minimum resource month and the combination of different renewable resources (hybrid systems) intrinsically takes into account the generation uncertainty and reduces the risk of lack of energy supply. Controllers are dimensioned depending directly on the installed generators. Generation systems could be located in every point of a certain area (thus not forcedly close to demand points as considered by [7]).

- Constraints of the *distribution system*: Every demand point must be connected to the generation system by an electric cable. The type of cable installed must satisfy maximum permitted voltage drop considering nominal distribution voltage, and cable resistance and maximum intensity. Microgrid structure is radial. Consumption meters must be installed in microgrids connecting multiple users.

Fig. 2 shows a solution to the AVEREMS problem in a community of 22 users distributed on an area of 1 km x 1 km. For each generation point, besides generators (indicated in Fig. 2), the number and type of the other components to be installed in the generation system, i.e. controllers, batteries and inverters (Fig. 1), must be specified. For each branch of a microgrid the type of cable must be specified in order to fulfill with distribution system constraints.

Please insert Figure 2

3. Enhanced deterministic heuristic

The deterministic heuristic proposed in [9] is considered as the starting point for the development of the proposed metaheuristic procedure. That heuristic is a fast method composed by 2 phases: first construction, and then a local optimization. In the "construction phase", the solution considering all independent generation points is firstly calculated, and then the algorithm iteratively extends microgrids as much as possible, according to the cost criterion. The "local optimization phase" is composed by 2 steps that are repeated if they improve the previously obtained solution (i.e., the solution cost is reduced): firstly the microgrids are divided into smaller ones and then the resulting microgrids are tried to be interconnected between them in a better way.

The "construction phase" in [9] has the following drawback. The microgrids are always created solving the minimum spanning tree problem [16], which, given a generation point and a set of users to connect, looks for the configuration of the distribution system that minimizes the cable length. However, this configuration does not ensure the minimum cost because it depends on both the cable length and the cable type (i.e. unitary cost) used in order to fulfil distribution system constraints, such as maximum permitted voltage drop. Thus, the cable type should also to be taken into account when deciding the distribution system.

In order to improve the original heuristic, we propose an enhanced deterministic heuristic based on the one proposed in [9]. The general scheme of the enhanced heuristic is shown in Figure 3 and the heuristic is described in the next sub-Sections. The original "construction phase" is modified in order to be easily adapted as the starting point of a meta-heuristic procedure (see Section 4). Moreover, we include an additional third phase, "distribution system optimization phase", which aims to reduce the distribution system cost. In that third phase, instead of using the minimal cable length distribution, longer lengths that may reduce the global solution cost are considered.

Sub-Section 3.1 lists and describes the internal functions used in the proposed enhanced heuristic. The description and reasoning of the "construction phase" and the "distribution system optimization phase" are presented in detail is sub-Section 3.2 and 3.3, respectively. The "local optimization phase" is equal to the one originally proposed in [9] and, therefore, it is not detailed here.

Please insert Figure 3

3.1 Internal functions

The internal functions used in the heuristic description are hereby reported. Some of these functions are defined to facilitate its posterior usage in the GRASP based algorithm described in Section 4. The functions use symbols defined in the “nomenclature” Section.

CM(*m*)	Cost of microgrid *m*, including all components of the generation and distribution systems.
CS(*s*)	Cost of solution *s*. $CS(s)=\sum_{m\in MS(s)} CM(m)$
LPA(*x*,*a*)	Minimum distance between point *x* and arch *a*
LPM(*x*,*m*)	Minimum distance between point *x* and microgrid *m* If $\lvert P(m)\rvert = 1$ then $LPM(x,m)=L(x,R(m))$ else $LPM(x,m)=\min_{a\in A(m)} LPA(x,a)$
LC(*m1*,*m2*)	Estimation of the cable extension required to connect microgrids *m1* and *m2*. $LC(m1,m2)=\delta\cdot\min\left(\min_{x\in P(m1)} LPM\left(x,m2\right),\ \min_{x\in P(m2)} LPM\left(x,m1\right)\right)$ δ is a coefficient used to take into account possible slight differences between microgrids’ distance and real cable extension. In the heuristic proposed in [9] δ=1 was assumed. In this study a value of δ=0.85 is considered in order to increase the possibility of connecting microgrids and thus to enlarge the search space of the algorithm.
BED(m)	Break Even Distance (*BED*) of microgrid *m*. It represents the maximum distance at which microgrid *m* could be reliably connected to another microgrid or to a no-demand generation point. Given *UCC* the lowest unitary cable cost [$/m] and *CC*(*m*) the total electric cable cost of microgrid *m*, $BED(m)=\frac{CM(m)-CC(m)}{UCC}$
B(*m*)	Set of branches of microgrid *m*. A branch is defined by the arches and the points (always including the generation point) of a microgrid that are downstream the same point, i.e. the electric energy they receive pass through the same arch connecting the generation point and a child of it (see Fig. 2).
MB(*B*)	Microgrid composed by the set of braches *B*
DU(*a*,*b*)	Set of users part of branch *b* that are downstream arch *a* (the electric energy they receive pass through arch *a*)
AB(*b*)	Set of arches of branch *b* sorted in a decreasing order by *PF(a)*, i.e. the product of arch length and the power flow circulating by it. For each $a \in AB(b)$, the parameter *PF(a)* is calculated as $PF(a)=L(a)\cdot\sum_{u\in DU(a,b)} PD(u)$
CB(b)	Cost of the cables of branch *b*. Cable connections within a branch follow a radial tree-scheme and are realized so that cable length is minimized using the classical shortest connection network algorithm [16]. The cable type with the minimum cost that fulfills with the maximum permitted voltage drop and the maximum flowing intensity is selected.
BD(*a*,*b*)	Set of 2 branches $\{BD_1(a,b), BD_2(a,b)\}$ resulting from removing arch *a* of branch *b*. Branch $BD_1(a,b)$ is composed by arches connecting all users *DU(a,b)*, while branch $BD_2(a,b)$ is composed by the arches connecting the rest of users

Split(*b*) Set of (1 or 2) branches that results after trying to eliminate one by one all arches of *b*. The function stops when a division is accepted because the distribution system cost is reduced. If no division is accepted then the function returns *b*. The algorithm of this function is reported in the following.

```
For ($a \in AB(b)$)
    If $CB(BD_1(a,b)) + CB(BD_2(a,b)) < CB(b)$ then
        return $\{BD_1(a,b), BD_2(a,b)\}$
    EndIf
EndFor
return $\{b\}$
```

ImproveCableCost(m) Function that tries to divide all the branches of microgrid m into smaller ones in order to reduce the distribution system cost. For each branch the following steps are carried out:

- It calculates the cost of dividing the branch into 2 smaller ones, eliminating one arch of the branch. All the arches are tried to be eliminated.
- If the cost of the 2 new branches is lower than the initial branch cost then the sub-division is accepted. Therefore the same subdivision process is carried out for the resulting 2 branches.
- The procedure stops when no more subdivision is accepted.

Let DB be the set of branches to be divided, b be the current branch that is tried to be divided and B* be the set of least cost branches. The detailed algorithm of this function is described in the following.

```
Initialize variables: $B^* = \emptyset$; $DB = B(m)$;
While ($DB \neq \emptyset$)
    $b$ = first element of $DB$; $DB = DB \setminus \{b\}$
    If ($Split(b) = \{b\}$) then $B^* = B^* \cup \{b\}$
    else $DB = DB \cup Split(b)$
EndWhile
Return $MB(B^*)$
```

In this function the generation point of microgrid *m* does not change. Thus $R(MB(B^*)) = R(m)$.

MR(*m*, *x*, *r*) Microgrid composed by *DP*(*m*) demand points with generation in point *x*. Cable length is firstly minimized using the shortest connection network algorithm [16].
If *r* = true: Cable cost is then improved utilizing the *ImproveCableCost(m)* function.
If *r* = false: Cable cost is not improved.

MU(*m1*,*m2*, *r*)	Microgrid (*mu*) that results after connecting (according to Prim’s algorithm [16]) all demand points of microgrids *m1* and *m2*. Therefore, $DP(mu) = DP(m1) \cup DP(m2)$ If *r* = true (cable cost is improved): The cable cost of *mu* is obtained utilizing the *ImproveCableCost(mu)* function; the root of microgrid *mu* is the one that leads to the lower cost between the root of *m1* and the root of *m2*: if *CM*(*MR*(*mu*,*R*(*m1*),true)) < *CM*(*MR*(*mu*,*R*(*m2*),true)) then *mu* = *MR*(*mu*,*R*(*m1*),true) otherwise *mu* = *MR*(*mu*,*R*(*m2*),true). If *r* = false (cable cost is not improved): *R*(*m2*) is selected as the root of *mu* only if it leads to a lower microgrid cost and has a Hybrid Potential Indicator (*HPI*) higher than *R*(*m1*): if *CM*(*MR*(*mu*,*R*(*m2*),false)) < *CM*(*MR*(*mu*,*R*(*m1*),false)) and *HPI*(*R*(*m2*)) > *HPI*(*R*(*m1*)) then *mu* = *MR*(*mu*,*R*(*m2*),false) otherwise *mu* = *MR*(*mu*,*R*(*m1*), false). *HPI*(*x*) is a resource indicator that considers the multiple renewable resources available in the area: higher the *HPI*(*x*) higher the resource(s) potential in point *x*. *HPI*(*x*) is calculated according to [17].
SelectM(*m*, *M*)	Returns the microgrid *mc* to be connected to microgrid *m*. *mc* is selected from set *M* of microgrids. The selected microgrid *mc* is $mc = \underset{z\in M \mid LC(z,m)\le max\left(BED(z),BED(m)\right)}{\arg\max}\left(\left(CM(m)+CM(z)\right)-CM\left(MU(m,z,\text{true})\right)\right)$
IGC(*s*, *ND*)	Returns the solution with generation in the best (low cost) demand point of each microgrid or in a no-demand point of set *ND*. For every microgrid *m* of solution *s*, the point *x* (part of the microgrid *m* or of set *ND*) that, if selected as the root, leads to the minimum microgrid cost is defined as microgrid generation point. In this function, set *ND* does not include no-demand points that are already the generation point of another microgrid part of solution *s*. $IGC(s,ND) = S\left(\bigcup_{m\in MS(s)} MR\left(m,\ \underset{x\in P(m)\cup ND}{\operatorname{argmin}}\left(CM\left(MR(m,x,\text{true})\right)\right),\text{true}\right)\right)$

3.2 Construction phase

The reasoning of the construction phase is the following. First, it is considered that all demand points are independent generation points (i.e., a solution without any microgrid). This is a trivial solution that may be a high cost solution. Then, the heuristic constructs iteratively the microgrids extending them as much as possible whenever the solution cost decreases. The microgrids are subsequently constructed in the following two iterative cycles, which are shown in Fig. 4:

1) Cycle 1: New microgrid construction iteration starts. The grid generation point of the (current) microgrid is firstly selected (STEP1) and then it starts cycle 2 in which the microgrid is extended.

2) Cycle 2: In each iterative step a microgrid (composed by one or more users) is tried to be connected to the current microgrid depending on certain criterion (STEP2). If the new microgrid has a lower cost than the two previous ones then the connection is accepted and Cycle 2 restarts. If the connection is not accepted then a new Cycle 1 starts.

The algorithm ends when all the demand points of the community are part of a created microgrid, i.e. a microgrid that was already tried to be extended.

Please insert Figure 4

The "selection steps" (STEP1 and STEP2 of Fig.4) are the most critical parts of the algorithm and are defined by two characteristics: the pool of possible candidates (PE_1, PE_2, respectively) and the indicator or heuristic function (HF_1, HF_2, respectively) used to rank the set PE and select the best candidate.

Regarding STEP1, the pool of possible candidate elements (PE_1) from which the microgrid generation point could be selected is the union of the sets of demand (D) and no-demand points (ND), not selected as a grid generation point in a previous iteration of cycle 1 (equation 1). As the number of initial no-demand points in an area could be considerably high, e.g. wind generation points are generally presented in form of a wide spatial grid with a spacing of 50 or 100 m, an "initial filter", proposed in [9], is firstly applied to pre-select most promising generation locations taking into account resource and demand distributions.

- $$PE_1 = D \cup ND \tag{1}$$

The heuristic function (HF_1) to rank the elements of the set PE_1 is the Grid Generation Score (GGS): an indicator that, based on demand and resource distributions, evaluates how much a certain point has the adequate characteristics for being the generation point of microgrid composed by multiple users (for more details see [17]). The point with the highest HF_1 (equation 2) is selected:

- $$HF_1(x) = GGS(x) \qquad \forall x \in PE_1 \tag{2}$$

Regarding STEP2, i.e. the selection of the microgrid to connect, being m the current microgrid in expansion, the pool of possible candidates (PE_2) is composed by all microgrids of the current solution s (excluding m) located at a distance from m lower than their Break Even Distance (BED) (equation 3).

$$PE_2 = \left\{ mc \in MS(s) \setminus \{m\} \middle| LC(mc,m) \le BED(mc) \right\} \tag{3}$$

The microgrid y that is tried to be connected to microgrid m could be selected in the following three different ways, adapted from [11]: HF_{2a}, HF_{2b} and HF_{2c} (equations 4, 5 and 6).

1) By distance (the element with the lowest HF_{2a} value is selected):

$$HF_{2a}(y) = LC(y,m) \qquad \forall y \in PE_2 \tag{4}$$

2) By *NGS*, *IGS* and distance (the element with the highest HF_{2b} value is selected):

$$HF_{2b}(y)=\frac{\max\limits_{py\in DP(y)}\left(1+NGS(py)-IGS(py);0.1\right)}{LC(y,m)}\qquad \forall y\in PE_2 \tag{5}$$

The *NGS* (No-generation Score) and the *IGS* (Independent Generation Score) are indicators that evaluate how much some a-priori characteristics of a point indicate that it should be a no-generation point (*NGS*) or an independent generation point (*IGS*) (for more details see [17]). As *NGS* and *IGS* can range from 0 to 2, a minimum value of the numerator is defined (0.1) in order to obtained always positive values of the HF_{2b}.

3) By savings (the element with the highest HF_{2c} value is selected):

$$HF_{2c}(y)=\left(\left(CM(m)+CM(y)\right)-CM\left(MU\left(m,y,\text{false}\right)\right)\right)\qquad \forall y\in PE_2 \tag{6}$$

As the heuristic function that leads to the best results is not always the same [9], the algorithm is launched three times, each time with one of the 3 HF_2, and finally the best found solution is returned.

3.3 Distribution system optimization phase

As it has been mentioned, when constructing the microgrids, the distribution is configured only considering the minimal cable length. However, since the cable costs are not taken into account, the minimal distribution cost is not ensured. The distribution cost may be reduced utilizing less expensive cables with a non-minimal cable length configuration and thus decreasing the total distribution cost.

This reduction is the objective of the proposed “Distribution system optimization phase”, which we apply to the solution returned by the “local optimization” phase (Fig. 3). The scheme of the third phase is shown in Fig. 5: firstly the branches of the microgrids of a previously obtained solution are tried to be subdivided, i.e. “Branches subdivision” (sub-Section 3.3.1) and then obtained microgrids are iteratively tried to be interconnected, i.e. “Microgrids interconexion” (sub-Section 3.3.2).

Please insert Figure 5

3.3.1 Branches subdivision

This step aims to improve the distribution system cost of the microgrids of the current solution by means of trying to subdivide the branches. Therefore, the function “*ImproveCableCost()*” is applied to every microgrid, as shown in the following.

Parameters

is	Initial solution
*M**	Set of least cost microgrids

Algorithm

```
1. $M^* = \bigcup_{m\in MS(is)} ImproveCableCost\ (m)$
```

```
2. Return $S(M^*)$
```

3.3.2 Microgrids interconnection

During this step the microgrids of the current solution are tried to be interconnected. For each microgrid *m* the following sub-steps are carried out:

- The microgrids located at distance to the microgrid (*m*) lower than their Break-Even Distance are tried to be connected (separately) to *m*. Next, in order to improve the distribution system, the "*ImproveCableCost()*" function is applied to each newly obtained microgrid. The microgrid *mc* that leads to the highest savings is selected.
- If the connection between microgrids *m* and *mc* decreases the cost of the solution then the two microgrids are connected and the algorithm tries to connect another microgrid to the latter obtained microgrid.
- This process stops when the connection is rejected (no cost improvement is obtained).

A detailed description of the procedure is reported in the following. As shown in Fig. 5, this algorithm is part of an iterative process.

<u>Parameters</u>

is	Initial solution
IM	Set of microgrids part of the initial solution *is* sorted by the number of connected points in descending order (in case of tie, by total cable length in descending order)
ND	Set of no-demand points pre-selected by the initial filter [9] as possible generation points
RM	Set of remaining microgrids that should be tried to be interconnected with the other microgrids
m	Current microgrid that is tried to be interconnected to the other microgrids
SM	Set of remaining microgrids that could be connected to *m*
mc	Selected microgrid to be connected to *m*
s	Current solution
sn	New solution obtained
AcceptCon	Boolean variable that indicates if the connection of microgrids *m* and *mc* is accepted or not
Continue	Boolean variable value that indicates if a new connection will be tried or not
*s**	Least cost solution

<u>Algorithm</u>

```
1. Initialization: $RM = IM$; $s^* = is$;
2. While ($RM \neq \emptyset$)
3.   $m$ = first element of $RM$; $RM = RM \setminus \{m\}$; $SM = MS(s^*) \setminus \{m\}$;
4.   $s = s^*$; $Continue = \exists mc \in SM \,|\, LC(mc, m) \leq \max\left(BED(mc), BED(m)\right)$
5.   While ($Continue$ and $SM \neq \emptyset$)
6.     Select the microgrid to be connected to m: $mc = SelectM(m, SM)$
7.     $m = MU(m, mc, \text{true})$; $SM = SM \setminus \{mc\}$; $sn = S(SM \cup \{m\})$
```

```
        Connection acceptance criterion: $AcceptCon = (CS(sn) < CS(s))$
        If ($AcceptCon$) then $s = sn$; $s^* = sn$; $RM = RM \setminus \{mc\}$; EndIf
        $Continue = AcceptCon$ and $\exists mc \in SM \,\middle|\, LC(mc,m) \le \max\left(BED\left(mc\right), BED(m)\right)$
    EndWhile
EndWhile
Improve generation cost: $s^* = IGC(s^*, ND)$
Return $s^*$
```

4. GRASP based algorithm

The enhanced deterministic heuristic described in Section 3 (from now on referred as the "deterministic heuristic") improves the performance of the previous deterministic heuristic proposed by [9], with a very small increase in the computational time, as verified in sub-Section 5.2. Nevertheless, when the improvement phases (second and third phases) are applied to the solution obtained in the construction phase, a local optimum is returned, which may not be the global optimal solution. Figure 6 shows a solution obtained in the construction phase (point "0"), and how it is led by the improvement phases to the basin of attraction of the valley at which point "0" belongs (a local optimum, point "1"). However, as shown in Fig. 6, the set of all possible feasible solutions is generally composed by multiple local optima [18]. Thus, it is not guaranteed the quality the solution generated by the enhanced deterministic heuristic in comparison with the global optimum.

In the last few decades, several meta-heuristic procedures have been developed in order to escape from local optima, which allows to explore better the solution space (i.e, to explore other valleys). Thus, better solutions may be found [11]. Among other metaheuristics, the Greedy Randomized Adaptive Search Procedure (GRASP) has been proposed [12]. GRASP is a multi-start metaheuristc. Specifically, GRASP generates different solutions at random (which may belong to different valleys) and improve them in order to obtain different local optima (see Fig. 6). As stopping criterion is usually defined a maximum calculation time or a maximum number of iterations. Obviously, the best local optimum found is returned.

Please insert Figure 6

GRASP has been successfully applied to many location optimization problems [13] including the capacitated plant location problem [14], which has many similarities with the AVEREMS problem (see [9]). Thus, we propose a GRASP based algorithm to solve AVEREMS.

In each iteration of the proposed GRASP algorithm, two phases are applied (Fig. 7): random solution construction and solution improvement (or local search) which starts at the constructed solution and applies iterative improvement until a local optimum is found. Repeated applications of the randomized construction procedure yields diverse starting solutions for the local search and the best overall solution obtained in the process is kept as the result.

Please insert Figure 7

In the following, we describe the new randomized solution construction (sub-Section 4.1) and the different proposed algorithm versions (sub-Section 4.2).

4.1 Randomized construction phase

The randomness of the GRASP is introduced in the solution construction phase in order to generate a wide range of different initial solutions and therefore improve the exploration of the solution space (Fig. 6). Assuming that a solution is composed by different elements that could be ranked by a heuristic function, the randomness can be introduced in the way these elements are selected [12]. As stated in sub-Section 3.2, microgrids can be seen as the different elements of a solution that are subsequently constructed in two iterative cycles (Fig. 4). Within each cycle there is a “selection step” (STEP1 and STEP2) in which the elements are ranked by a heuristic function and then the best ranked element is selected. Instead of selecting the best element, two restricted candidate lists (RCLs) could be used in STEP1 and STEP2 in order to introduce randomization:

1) *RCL1*: list for the selection of the microgrid generation point (STEP1).
2) *RCL2*: list for the selection of the microgrid that is tried to be connected (STEP2).

In the classical GRASP implementation [12], a single RCL is used. Hereby two RCLs are considered in order to increase the randomization effect, enhance the variability of the constructed solutions and thus enlarge the exploration of the solution space.

The main characteristics of the RCLs are: the pool of possible candidates, the size (nº of elements) of the RCL, the heuristic function and the selection procedure. These characteristic for RCL1 and RCL2 are reported in Table 1 and next described:

a) The pool of possible candidates for STEP1 and STEP2 (respectively PE_1 and PE_2) are defined in sub-Section 3.2 (equations 1 and 3).

b) Regarding the size, the number of best ranked elements (according to their heuristic function) to be included in the RCL could be defined as [19]:

$$SE = \max\left(\left[\alpha \cdot |PE|\right], 1\right) \text{ where } 0 \leq \alpha \leq 1 \qquad (7)$$

Note that if $\alpha = 0$ then the selection is deterministic (i.e. the best ranked element is always selected), while as α increases higher will be the randomness of the selection (with $\alpha = 1$ the highest randomness is achieved). The appropriate choice of the value of parameter α is clearly critical and relevant in order to achieve a good balance between computation time and solution quality [20]. Parameter α will be calibrated for both RCL1 and RCL2 (sub-Section 5.3.1).

c) The heuristic functions (*HF*) used in STEP1 and STEP2 are defined in sub-Section 3.2. There is a single HF_1 for STEP1 (equation 2), while there are three possible HF_2 (HF_{2a}, HF_{2b}, HF_{2c}, defined in equations 4, 5 and 6) for STEP2.

d) Regarding the selection procedure, in the original GRASP the selection of an element from the RCL is done in a uniform random way: all elements of the list have the same probability to be chosen [12]. However, later studies showed that better results can be achieved by a random biased selection, in which the probability of selecting a certain element is proportional (or inversely proportional) to its heuristic function [21]. Therefore, being HF_i the value of the heuristic function for element i, the selection probability p_i of element i from a RCL is calculated as:

- Proportional selection (P): $$p = \frac{HF_i}{\sum_{y \in RCL} HF_y} \tag{8}$$
- Inversely proportional selection (IP): $$p_i = \frac{1/HF_i}{\sum_{y \in RCL} 1/HF_y} \tag{9}$$

The set RCL is composed by the SE best ranked elements of the pool of possible candidates (PE). Elements are sorted by their HF value in a decreasing or increasing order in the case of respectively proportional or inversely proportional selection.

Please insert Table 1

4.2 Different algorithm versions

As shown, there are three heuristic functions for STEP2 (HF_{2a}, HF_{2b}, and HF_{2c}). The heuristic function that obtains the best results cannot be defined a-priori. Therefore, we propose to analyze the performance of the following 5 GRASP based algorithm versions:

- GRASP1: HF_{2a} is always applied in each STEP2
- GRASP2: HF_{2b} is always applied in each STEP2
- GRASP3: HF_{2c} is always applied in each STEP2
- GRASP4: HF_{2a}, HF_{2b} or HF_{2c} are randomly selected (with the same probability) in each STEP2 of the construction phase.
- GRASP5: HF_{2a}, HF_{2b} or HF_{2c} are alternatively applied in each GRASP iteration.

Furthermore, another algorithm version (GRASP0) in which the selection of the microgrid generation point (RCL1) and the selection of the microgrid to be connected (RCL2) are totally random, i.e. $\alpha_1 = \alpha_2 = 1$ and $HF_1 = HF_2 =$ constant (e.g. 1), is also analyzed in order to evaluate the importance of utilizing good heuristic functions. The performances of these algorithm versions are compared in Section 5.

5. Computational experiment

In the previous Sections, an enhanced deterministic heuristic (Section 3) and then a GRASP based procedure (Section 4) were presented in order to support the design of autonomous community rural electrification projects based on renewable energies considering a combination of independent generation points and microgrids.

Hereby, we carried out a computational experiment in order to analyze the performance of the proposed algorithms. The analyzed instances are firstly described in sub-Section 5.1; then the improvements of the enhanced deterministic heuristic in comparison with the previous one [9] are analyzed (sub-Section 5.2); in sub-Section 5.3 the different GRASP based algorithm versions are calibrated and finally the performance of the best version is evaluated in comparison with the procedure available in literature (sub-Section 5.4). All calculations were done on a PC Intel Core 2 i7-2600 3.4 GHz with 8 GB of RAM. The code and the results obtained with the best GRASP version are available in [22].

5.1 Analyzed instances

The same instances utilized in [9] are used: the complete input data are available in [22]. The instances were randomly generated based on the characteristics of the following 5 real rural electrification projects: El Alumbre (Peru), Alto Perú (Peru), Achada Leite (Cape Verde), El Roblar (Nicaragua) and Sonzapote (Nicaragua). Real projects resource data are utilized in order to generate the instances: solar resource was estimated by NASA database [23], while the wind resource map of the area (with a grid spacing of 100 m) was obtained using a micro-scale wind flow model [5].

The electricity requirements of each user (household) are 420Wh/day and 300W of energy and power demand respectively. Regarding electrical equipments, the following data were considered:

- Wind turbines (4 types): nominal power: 100 W to 2000 W; cost (including controllers): \$1394 to \$8732.
- PV panels (3 types): nominal power: 50 W to100 W, cost: \$451 to \$821.
- PV controller (3 types): maximum power: 50 W to 100 W, cost: \$67 to \$95.
- Batteries (4 types): capacity: 1500 Wh to 3000 Wh; cost: \$225 to \$325; efficiency 85%; maximum discharge rate: 0.6; autonomy: 2 days.
- Inverters (4 types): maximum power: 300 W to 3000 W; cost: \$377 to \$2300; efficiency 85%.
- Electric cables (2 types): cost: \$4.9/m and \$5.1/m; resistance: 2.71 and 2.15 Ω/km; maximum intensity: 89 and 101 A; nominal voltage: 220 V; minimum voltage: 220 V; maximum voltage: 230 V.
- User consumption meter: cost: \$50 (installed only in microgrids composed by multiple users).

The instances have a variable number of users (ranging from 10 to 90) and, regarding users' distribution, they were randomly generated considering two different concentrations (last row of Table 2). According to the characteristics described in Table 2, two set of instances were generated: a "training set" of 90 instances for the calibration of the internal parameters used by the developed procedures and a "test set" of 450 instances for comparing the performance of the developed procedures.

Please insert Table 2

5.2 Performance of the enhanced deterministic heuristic

The solutions of the enhanced deterministic heuristic described in Section 3 ("enhanced deterministic heuristic" or "EDH") are compared with those obtained by the previous deterministic heuristic [9] ("initial deterministic heuristic" or "IDH"). The results of the comparison between the 2 algorithms in the test set of 450 instances are shown in Table 3: columns 3 to 6 show the mean solution cost ("cost") and mean computation times ("time") of the IDH and the EDH for different groups of instances; columns 7 shows the % of the difference between mean solution costs; column 8 and 9 indicate respectively the number of instances (in percentage) in which EDH improves the IDH of more than 1% and vice versa (in the rest of instances the differences between solutions of the 2 algorithms are lower than 1%).

The improvement of the enhanced heuristic is highly related with the number of users of the community (Table 3), i.e. the complexity of the instance to be solved. The effect of including the cable optimization phase is almost null for communities up to 30 users in which initial heuristic were found to be close to the optimal, according to [9]. The improvement of the EDH in comparison with the IDH increases rapidly as the number of users increases: for communities of more than 60 users significant improvements (more than 1%) of the EDH are found in 20% of the instances, whereas significant improvements of the IDH were found in less than 3% of the instances. The total mean solution costs of the IDH and the EDH are 87615$ and 87392$ respectively: the slight increase in calculation time is compensated by the solution improvement obtained by the enhanced deterministic heuristic.

<u>Please insert Table 3</u>

5.3 Selection of best GRASP based algorithm version

As stated in sub-Section 4.2, different algorithm versions (based on the GRASP) should be analyzed, depending on the heuristic function utilized in the selection of the microgrid that is tried to be connected. In this Section all versions are firstly calibrated (Section 5.3.1) and then performances are compared in order to select the best one (Section 5.3.2).

5.3.1 Calibration of the algorithms

As stated in sub-Section 4.2, the value of parameter α, i.e. the ratio of possible candidates included in the RCL, is highly relevant in order to achieve a good balance between computational time and solution quality of a GRASP. Therefore, the parameters $\alpha_1 = 0, 0.2, \ldots, 1$ and $\alpha_2 = 0, 0.2, \ldots, 1$ are calibrated, i.e. all combinations of values are tried, for the different algorithm versions on the "training set" of 90 instances. A computational time of 800 s is considered for each instance. The combinations of values that lead to the best (mean lowest cost) solutions are reported in Table 4.

<u>Please insert Table 4</u>

5.3.2 Comparison of different algorithm versions

Hereby, the 5 algorithm versions (GRASP1 to GRASP5) together with GRASP0 are compared and their results on the “test set” of 450 instances are shown in Fig. 8 and Table 5. Fig. 8 shows the convergence curves, i.e. the evolution of the cost of the best solution obtained by each version over the computational time. Each point of these curves is the mean value of the solution costs in the 450 instances at different computational times. For each GRASP version, Table 5 shows the mean solution cost obtained with 3600 s (column 2) and the percentage of instances for which each version finds a solution that is less than 1% worse than the best solution obtained by the 6 versions (column 3).

Please insert Figure 8

Please insert Table 5

The version that does not use any heuristic function (GRASP0) obtains the worst results: its mean solution cost is higher than 87000$ (while all other versions are below 86800$) and its convergence curve is always above all the others. This confirms the importance of utilizing good heuristic functions for the selection of the elements in the RCLs.

The convergence curves of the other algorithm versions (GRASP1 to GRASP5) have a similar pattern: most of the improvement is reached in the first 1000 s (dotted line in Fig. 8) whereas afterwards the curves tend to be horizontal (asymptotes). GRASP1 and GRASP2 obtain better results in comparison with GRASP3, possibly because the calculation for the savings (HF_{2c}) requires longer computational time than the other heuristic functions (HF_{2a} and HF_{2b}). However the versions that utilize the 3 heuristic functions (GRASP4 and GRASP5), taking advantage of the benefits of each one, are better options. GRASP4 (in which the HF utilized in each launch of RCL2 is randomly selected between HF_{2a}, HF_{2b} and HF_{2c}) is the best version: its convergence curve is always below all the others, its final mean solution cost is the lowest one (86666$) and it obtains the best solution in more instances (99.8%) than GRASP5 (99.1%).

Therefore, the version GRASP4 is selected as the proposed solving procedure of this study.

5.4 Performance of the GRASP based procedure

As introduced, the only known algorithm that solves the AVEREMS problem thus designing off-grid electrification projects based on renewable energies considering micro-scale resource variations, a combination of independent generation points and microgrids and generation far from demand points is the deterministic heuristic proposed by [9] (called “IDH”). A preliminary computational experiment showed that the solutions of that algorithm considerably improve the solutions obtained by other procedures that, with some limitations, deal with the same design problem: the mathematical model proposed by Ferrer-Martí et al. [7] and the VIPOR software [10]. Considering the same assumptions and set of instances used in [9], it was verified that the proposed GRASP based procedure highly enhances the solutions obtained by those procedures: mean improvements of around 7% and 6% are obtained, respectively, with the mathematical model proposed in [7] and the VIPOR software [10]. An enhanced version of the IDH (called

“EDH”) was proposed in Section 3 that improves the performance of the IDH, as shown in sub-Section 5.2.

The solutions of the proposed GRASP based procedure (“GRASP” refers to GRASP4, i.e. the best algorithm version) are now compared with the ones obtained by the enhanced deterministic heuristic (EDH). As shown in Fig. 8, the enhanced heuristic (full black circle) can rapidly obtain a good solution (29 s), slightly better than the one obtained by the GRASP (blue line) in the same computational time (the same solution is reached by the GRASP after 70 s). However, when a higher computational time is available, as it is expected when dealing with the design of a long-term project, the proposed GRASP can considerably enhance the solutions obtained by the EDH.

Table 6 presents the comparison between solutions obtained by the EDH and the GRASP (with a computational time of 3600 s) in the analyzed instances. The EDH and GRASP mean solution costs and computational times are shown in columns 3-4 and 5-6 respectively. Besides the mean difference between both solutions (column 7), the percentage of instances in which GRASP improves EDH solution of more than 1% (column 8) is presented (mention that GRASP improves EDH in all instances except one in which GRASP solution is 0.1% worse than EDH solution).

<u>Please insert Table 6</u>

The improvement of the GRASP in comparison with EDH depends on the number of users of the community (Fig. 9), the size of community area and the type of users’ concentration:

- As the number of users of the instance increases also the differences between EDH and GRASP increase (Fig. 9). For instance of more than 30 users GRASP enhances EDH of more than 1% in more than 20% of the instances. In instances between 70 and 90 users the mean improvement is around 1%.
- As smaller the community area higher the improvement: the lowest improvements (0.4% and 0.3% respectively) are obtained in instances C1 and C5 that where users are dispersed over widest areas (12.25 and 16 km^2 respectively), while highest improvements (1.1%) are obtained in C3 that has the smallest area of just 4 km^2.
- Higher improvements are obtained in instances with higher users’ concentration: significant enhancements (more than 1%) are obtained in respectively 22% and 33% of the instances for the low and high users’ concentration types.

<u>Please insert Figure 9</u>

Fig. 10 shows the computational time and the number of iterations at which the GRASP reaches the asymptote, i.e. the point at which 90% of the final improvement (after 3600 s) to EDH is obtained. The computational time before reaching the asymptote increases as the number of users increases: in instances up to 60 users the asymptote is reached in less than 600 s. However, even in instances of 90 users, 90% of the final improvement is obtained in slightly more than half of the computational time (2000s over 3600s). This indicates that a computational time of 1 hour can be considered sufficient to get the most out of the GRASP in the analyzed instances.

Regarding the number of iterations before reaching the asymptote, Fig. 10 shows that this value is not that affected by the number of users of the instances. In most cases, the asymptote is reached after between 50 and 200 iterations. Thus when applying the algorithm for the design, a maximum number of iteration can be established as a stopping criterion of the GRASP based algorithm: a value above 200 iterations seems to be adequate in order to get the most out of the algorithm.

Please insert Figure 10

In order to illustrate the type of solutions obtained, Fig. 11 shows the solution of the developed GRASP based method in a community of 88 users in Nicaragua [24]. The proposed configuration combines independent systems (P0, P1, P2 and P3) with wind (Microgrid 1) and solar (Microgrid 2 and 3) microgrids that connect concentrated groups of users taking advantage of the best wind resource area (red area). It reduces the cost of the project more than 15% in comparison with a design configuration considering all independent generation points.

Please insert Figure 11

6. Conclusions

This study presents an enhanced deterministic heuristic and a meta-heuristic procedure to design rural communities' off-grid electrification projects based on renewable energies. The proposed methods consider the design of multiple microgrids and independent users, the use of hybrid systems combining different renewable energies, micro-scale resource variations and the installation of generators far from demand points.

Firstly, some enhancements to an existing deterministic algorithm proposed in a recent publication are presented. The new procedure improves solutions obtained by the previous method with a minimal increase in computational time. Based on this new heuristic, a GRASP based method is proposed in order to escape from local optima where the deterministic heuristic can remain trapped. Different algorithm versions were calibrated and compared in order to select the best one.

The performance of the proposed algorithms was tested on 450 instances from literature, generated according to real projects, with different number of users (from 10 to 90), users' concentrations and available wind and solar resources.

The new deterministic heuristic can rapidly obtain a good solution in less than 1 minute in most analyzed instances. On the other hand, the proposed GRASP based algorithm considerably enhances solutions obtained by the deterministic heuristic with a computational time of 1 hour on a standard PC, a lapse of time generally affordable taking into account the problem to be solved. This improvement tends to increase as the number and the concentration of users increases: significant improvements (higher than 1%) were obtained in more than 30% of the instances bigger than 40 users.

The proposed algorithm is a complete design tool that can efficiently support the design of stand-alone community electrification projects requiring of low computational resources. A possible future line of research could be the explicit consideration in the model of the uncertainty in the renewable energy generation.

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Appendix A – A mathematical model to solve the AVEREMS problem

The mathematical formulation of the mathematical model presented in [7] considering wind and solar energies is hereby reported.

Data

Consumption points:

P	Number of consumption points (households, schools, health centers, community centers, etc.). These are the only points where the generators can be placed.
L_{pd}	Distance [m] between two points p and d (p= 1,…, P; d = 1,…, P).
L_{max}	Maximum allowed length of segment of a cable of the microgrid.
Q_p	Set of points to which a point p could be directly joined with a cable segment (p= 1,…, P): $Q_p = \{d = 1,...,P : p \neq d \wedge L_{pd} \leq L_{max}\}$.
ED_p	Electric energy demand [Wh/day] at p (p = 1,…, P).
PD_p	Power demand [W] at p (p = 1,…, P).
CM	Cost [US$] of an electric meter.

Wind Generation:

A, NA	Types of wind turbines (a = 1,…, A) and maximum number of wind turbines that can be placed at a point, respectively.
EA_{pa},	Energy generated [Wh/day] by a wind turbine placed at point p of type a (p = 1,…, P; a = 1,…, A).
PA_a	Maximum power [W] of a wind turbine of type a (a = 1,…, A).
CA_a	Cost [US$] of a wind turbine of type a (a = 1,…, A).
R	Types of battery charge wind controllers (r = 1,…, R).

PR_r	Maximum power [W] of a battery charge wind controller of type r ($r = 1,\ldots, R$).
CR_r	Cost [US$] of a battery charge wind controller of type r ($r = 1,\ldots, R$).

PV Generation:

S, NS	Types of PV panels ($s = 1,\ldots, S$) and the maximum number of PV panels that can be placed at a point, respectively.
ES_s,	Energy generated [Wh/day] by a PV panel of type s ($s = 1,\ldots, S$).
PS_s	Maximum power [W] of a PV panel of type s ($s = 1,\ldots, S$).
CS_s	Cost [US$] of a PV panel of type s ($s = 1,\ldots, S$).
Z	Types of PV battery charge controllers ($z = 1,\ldots, Z$).
PZ_z	Maximum power [W] of a battery charge PV controller of type z ($z = 1,\ldots, Z$).
CZ_z	Cost [US$] of a battery charge PV controller of type z ($z = 1,\ldots, Z$).

Energy storage:

B	Types of batteries ($b = 1,\ldots, B$).
ηb	Efficiency of the batteries [fraction of unity].
DB	Maximum proportion of discharge admitted in the batteries.
VB	Required autonomy of the batteries [days].
EB_b	Capacity [Wh] of a battery of type b ($b = 1,\ldots, B$).
CB_b	Cost [US$] of a battery of type b ($b = 1,\ldots, B$).
I	Types of inverters ($i = 1,\ldots, I$).
ηi	Efficiency of the inverters [fraction of unity].
PI_i	Maximum power [W] of an inverter of type i ($i = 1,\ldots, I$).
CI_i	Cost [US$] of an inverter of type i ($i = 1,\ldots, I$).

Microgrid:

C	Types of microgrid cables.
RC_c	Electric resistance (feed and return) [Ω/m] of a cable of type c ($c = 1,\ldots, C$).
IC_c	Maximum intensity [A] of a cable of type c ($c = 1,\ldots, C$).
CC_c	Cost [US$/m] of a cable of type c, including the cost of the infrastructure ($c = 1,\ldots, C$).
V_N ,V_{min},V_{max}	Nominal, Minimum and Maximum voltage [v], respectively.
ηc	Efficiency of the microgrid [fraction of unity].

Variables

The model has the following variables:

- Integer non-negative variables to define the location and sizing of equipment:

xa_{pa}	Number of wind turbines of type a placed at point p ($p = 1,\ldots,P;\ a = 1,\ldots,A$).
xs_{ps}	Number of PV panels of type s placed at point p ($p = 1,\ldots,P; s = 1,\ldots,S$).
xb_{pb}	Number of batteries of the type b placed at point p ($p = 1,\ldots,P; b = 1,\ldots,B$).
xr_{pr}	Number of battery charge wind controllers of type r placed at point p ($p = 1,\ldots,P; r = 1,\ldots,R$).
xi_{pi}	Number of inverters of the type i placed at point p ($p = 1,\ldots,P; i = 1,\ldots,I$).
xz_{pz}	Number of battery charge PV controllers of type z placed at point p ($p = 1,\ldots,P; z = 1,\ldots,Z$).

- Float non-negative variables to define energy and power flows and voltage:

fe_{pd} Flow of energy [Wh/day] between points p and d ($p = 1,...,P; d \in Q_p$).

fp_{pd} Flow of power [W] between points p and d ($p = 1,...,P; d \in Q_p$).

v_p Voltage [V] at point p ($v_p = V_{min},...,V_{max}; p = 1,...,P$).

- Binary variables to define the generation points, the microgrid and the meters:

$xg_p \in \{0,1\}$ 1 if some wind turbine and/or PV panel is placed at point p ($p = 1,...,P$); otherwise.

$xc_{pdc} \in \{0,1\}$ 1 if there is a cable of type c between the points p and d ($p = 1,...,P; d \in Q_p; c = 1,...,C$); 0 otherwise.

$xm_p \in \{0,1\}$ 1 if an electric meter is placed at point p ($p = 1,...,P$); 0 otherwise.

Objective function

The objective function (10) minimizes the capital cost; i.e., the total cost of the generation, storage and distribution equipment.

$$\begin{aligned}[MIN] Z = {} & \sum_{p=1}^{P}\sum_{a=1}^{A} CA_a \cdot xa_{pa} + \sum_{p=1}^{P}\sum_{s=1}^{S} CS_s \cdot xs_{ps} + \sum_{p=1}^{P}\sum_{b=1}^{B} CB_b \cdot xb_{pb} + \\ & \sum_{p=1}^{P}\sum_{d \in Q_p}\sum_{c=1}^{C} L_{pd} \cdot CC_c \cdot xc_{pdc} + \sum_{p=1}^{P}\sum_{i=1}^{I} CI_i \cdot xi_{pi} + \\ & \sum_{p=1}^{P}\sum_{r=1}^{R} CR_r \cdot xr_{pr} + \sum_{p=1}^{P}\sum_{z=1}^{Z} CZ_z \cdot xz_{pz} + \sum_{p=1}^{P} CM \cdot xm_p \end{aligned} \tag{10}$$

Constraints

Constraint (11) defines the points at which wind turbines are placed and limits the maximum number of generators at the same point; in an analogous way (12) incorporates PV panels. Constraint (13) forces xg_p to be equal to 0 if neither a wind turbine nor a PV panel is placed at point p. Energy and power balances and conservation are described in (14) and (15), respectively. Constraint (16) establishes the capacity of the batteries. Constraints (17) and (18) relate the energy and power flows respectively, to the existence of a cable between two points. The radial distribution of the microgrid is established in (19), constraint (20) limits the voltage drops and (21) the maximum intensity. The power of battery charge wind controllers is defined in (22). In a similar way, the power of battery charge solar controllers is defined depending on the power of the corresponding PV panel (23). Inverters can only be placed at points where wind-PV generators are placed (24). Constraints (25) and (26) force the installation of electric meters at the consumption points fed by a microgrid.

$$\sum_{a=1}^{A} xa_{pa} \le NA \cdot xg_p \qquad p = 1,...,P \tag{11}$$

$$\sum_{s=1}^{S} xs_{ps} \le NS \cdot xg_p \qquad p = 1,...,P \tag{12}$$

$$\sum_{a=1}^{A} xa_{pa} + \sum_{s=1}^{S} xs_{ps} \geq xg_{p} \qquad p = 1,\dots,P \tag{13}$$

$$\sum_{q=1|p\in Q_q}^{P} fe_{qp} + \sum_{a=1}^{A} EA_{pa}\cdot xa_{pa} + \sum_{s=1}^{S} ES_{s}\cdot xs_{ps} \geq \frac{ED_p}{\eta b\cdot \eta i}\left(\frac{1}{\eta c} + \left(1-\frac{1}{\eta c}\right)xg_p\right) + \sum_{d\in Q_p} fe_{pd} \qquad p = 1,..,P \tag{14}$$

$$\sum_{q=1|p\in Q_q}^{P} fp_{qp} + \sum_{i=1}^{I} PI_i\cdot xi_{pi} \geq PD_p\left(\frac{1}{\eta c} + \left(1-\frac{1}{\eta c}\right)xg_p\right) + \sum_{d\in Q_p} fp_{pd} \qquad p = 1,\dots,P \tag{15}$$

$$\sum_{b=1}^{B} EB_b\cdot xb_{pb} + \left(\frac{VB}{DB}\sum_{j=1}^{P}\frac{ED_j}{\eta b\cdot\eta i\cdot\eta c}\right)\left(1-xg_p\right) \geq \frac{VB}{DB}\left(\sum_{d\in Q_p} fe_{pd} + ED_p\right) \qquad p = 1,\dots,P \tag{16}$$

$$fe_{pd} \leq \left(\sum_{j=1}^{P}\frac{ED_j}{\eta b\cdot\eta i\cdot\eta c}\right)\sum_{c=1}^{C} xc_{pdc} \qquad p = 1,\dots,P;\, d\in Q_p \tag{17}$$

$$fp_{pd} \leq \left(\sum_{j=1}^{P}\frac{PD_j}{\eta c}\right)\sum_{c=1}^{C} xc_{pdc} \qquad p = 1,\dots,P;\, d\in Q_p \tag{18}$$

$$\sum_{q=1|p\in Q_q}^{P}\sum_{c=1}^{C} xc_{qpc} + xg_p \leq 1 \qquad p = 1,\dots,P \tag{19}$$

$$v_p - v_d \geq \frac{L_{pd}\cdot RC_c\cdot fp_{pd}}{V_n} - \left(V_{max} - V_{min}\right)(1 - xc_{pdc}) \qquad p = 1,\dots,P;\, d\in Q_p;\, c = 1,\dots,C \tag{20}$$

$$\frac{fp_{pd}}{V_n} - \left(\sum_{j=1}^{P}\frac{PD_j}{V_{min}\cdot\eta c}\right)(1 - xc_{pdc}) \leq IC_c \qquad p = 1,\dots,P;\, d\in Q_p;\, c = 1,\dots,C \tag{21}$$

$$\sum_{r=1}^{R} PR_r\cdot xr_{pr} \geq \sum_{a=1}^{A} PA_a\cdot xa_{pa} \qquad p = 1,\dots,P \tag{22}$$

$$\sum_{z=1}^{Z} PZ_z\cdot xz_{pz} \geq \sum_{s=1}^{S} PS_s\cdot xs_{ps} \qquad p = 1,\dots,P \tag{23}$$

$$xi_{pi} \leq NI\cdot xg_p \qquad p = 1,\dots,P;\, i = 1,\dots,I \tag{24}$$

$$\sum_{d\in Q_p}\sum_{c=1}^{C} xc_{pdc} \leq (P-1)\; xm_p \qquad p = 1,\dots,P \tag{25}$$

$$\sum_{q=1|p\in Q_q}^{P}\sum_{c=1}^{C} xc_{qpc} \leq xm_p \qquad p = 1,\dots,P \tag{26}$$

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Abstract

The design of off-grid electrification projects considering hybrid systems and distribution microgrids is a complex task that requires the use of decision support tools. Most of existing tools focus on the design of hybrid systems without defining generator locations and microgrids configuration. Recently a deterministic heuristic was developed to solve the problem. In this study we present an enhanced deterministic heuristic and then a meta-heuristic procedure for designing community off-grid electrification projects based on renewable energies considering micro-scale resource variations and a combination of independent generation points and microgrids. Both new algorithms improve performance of the previous existing procedure. The new deterministic heuristic can rapidly (in a computational time lower than 1 minute) obtain a good solution. On the other hand, the proposed meta-heuristic method considerably enhances solutions obtained by the deterministic heuristic with a computational time of 1 hour on a standard PC. The improvement tends to raise as the complexity of the analyzed instance increases. The proposed algorithm is a complete design tool that can efficiently support the design of stand-alone community electrification projects requiring of low computational resources.

Nomenclature

- *A*(*m*): Set of arches of microgrid *m*
- *AVEREMS*: Autonomous Village Electrification through Renewable Energy and Microgrid Systems
- *DP*(*m*): Set of demand points of microgrid *m*
- *GGS*: Grid Generation Score
- *GRASP*: Greedy Randomized Adaptive Search Procedure
- *IGS*: Independent Generation Score
- *L*(*x*,*y*): Euclidean distance between point *x* and *y*
- *LA*(*a*): Length of arch *a*
- *MS*(*s*): Set of microgrids of solution *s*
- *NGS*: No-generation Score
- *P*(*m*): Set of points of microgrid *m*
- *PD*(*u*): Electrical power demand of user *u*
- *RCL*: Restricted Candidate List (of the GRASP)
- *R*(*m*): Generation point (root) of microgrid *m*
- *S*(*M*): Solution composed by microgrids of set *M*

1. Introduction

Projects relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously [1]. These systems produce electricity in a clean way, their cost is often lower than national grid extension and they are not dependent from continuous fuel supply (such as diesel generators), therefore increasing projects long-term sustainability [2]. In this context, the configurations that proved to be the most reliable design options are hybrid systems that combine different generation resources [3] and distribution microgrids, where the energy is produced in a certain point and distributed through an electric microgrid to other consumption points [4].

The design of off-grid renewable energy projects considering hybrid systems and distribution microgrids must consider multiple issues. When designing hybrid systems, the most adequate combination of technologies should be evaluated depending on available resources and generation and storage equipments characteristics. When designing microgrids, the selection of grid generation points and the definition of which points should be connected to a certain micro-grid and which not are complex tasks, especially when a resource (e.g. wind) is highly disperse [5] and best areas for installing generators could be located far from demand points [6]. Furthermore, in scattered communities with isolated users, the combination of multiple microgrids and independent generation points is generally the cheapest design solution [7].

Over last decade, many tools have been developed in order to support the design [8]. However, most of them define the best combination of energy resources in one point but without designing the distribution through microgrids and without taking into account resource spatial variations. The only known method that permits the design of off-grid electrification projects based on multiple renewable energies considering micro-scale resource variations, a combination of independent generation points and microgrids and considering generation in every point of an area (not only close to the users) is the deterministic greedy heuristic proposed in [9].

The problem solved is called AVEREMS: the Autonomous Village Electrification through Renewable Energy and Microgrid Systems [9]. The solutions of that algorithm were shown to considerably improve those obtained by other procedures that, with some limitations, deal with the same design problem: VIPOR software [10] and the mathematical model presented in [7]. However, the algorithm proposed by [9] has some possible weaknesses. Firstly, it creates microgrids always minimizing cable length, while in some cases it would be preferable to utilize a different network configuration in order to reduce utilized cable unitary cost and thus microgrid cost. Furthermore, it is a deterministic procedure in which a single solution is greedily constructed and then improved by a local search phase. It should be noted that the solution obtained by the local search, i.e. local optimum, could be far from the global optimum, i.e. the best of all feasible solutions.

In the last few decades, various meta-heuristic procedures have been developed in order to escape from local optima and thus improve solutions encountered by deterministic heuristics [11]. One of those is the GRASP (Greedy Randomized Adaptive Search Procedure) [12] that has been successfully applied to various location optimization problems [13]. In particular, a GRASP based procedure demonstrated to be highly efficient in solving the capacitated plant location problem [14],which has various similarities with the AVEREMS problem (see [9]).

In this study we present an improved deterministic heuristic and then a meta-heuristic procedure, based on the GRASP, for solving the AVEREMS problem; that is, for designing community off-grid electrification projects based on renewable energies considering micro-scale resource variations and a combination of independent generation points and microgrids. The contribution of the paper is to propose an algorithm that obtains better results than currently available procedures with low computational requirements. In this paper the first meta-heuristic algorithm specifically designed for this purpose is proposed while previous methods were based on simpler procedures. The proposed methods consider the design of multiple microgrids and independent users, the use of hybrid systems combining different renewable energies and the installation of generators far from demand points.

The rest of the paper is organized as follows. Section 2 presents the components of a general off-grid electrification project and the basic problem statement of the AVEREMS. An enhancement to the deterministic heuristic method described in [9] is proposed in Section 3. Various versions of the proposed GRASP based algorithm are described in detail in Section 4. In Section 5 the best version is identified and its performance is compared with the existing procedure. Section 6 deals with the conclusions.

2. The AVEREMS problem

In this Section, after defining the main glossary used (sub-Section 2.1), the components of a hybrid off-grid electrification system (sub-Section 2.2) and the AVEREMS problem are described (sub-Section 2.3).

2.1 Glossary

The main terms used to describe the problem and the methods proposed in Sections 3 and 4 are hereby defined:

- Demand point (or user): location of a consumption point, such as a house or a public building, with certain electric energy and power demands. Demand points can be generation points.
- Distribution system: the electric cables that connect the generation system to the users.
- Generation point: location where a generation system is installed.
- Generation system: group of components installed in a certain point in order to generate and store the electricity. It includes generators (wind turbines and solar panels), controllers, batteries and inverters.
- Grid consumption point (or no-generation point): a user connected to a multiple points' microgrid and not being the generation point. It just consumes energy.
- Grid generation point: generation point of a microgrid composed by multiple points
- Independent generation point (or independent generation system): a user that is producing energy just for its own consumption.
- Microgrid: set of one or more users fed by a generation system placed in a demand or no-demand point. It includes both the generation and the distribution systems.
- No-demand point: location (that is not a demand point) that can be a generation point.

2.2 Components of an off-grid electrification system

The scheme of the elements involved in an autonomous electrification system considering wind and solar energies is as follows (Fig. 1):

1) Generators: produce energy in alternating (wind turbines) or direct (solar panels) current.
2) Controllers: convert to direct current and control the charge/discharge of the batteries.
3) Batteries: store the energy produced by the generators, receive and supply electricity at direct current.
4) Inverters: convert direct to alternating current at the nominal voltage.
5) Electric cables: configure the microgrid that distributes the energy (only low voltage distribution is considered).

6) Electric meters: measure the energy consumed at the demand points.
7) Users (or Demand points): consume the energy.

Please insert Figure 1

The generation system is composed by the generators (wind turbines and/or solar panels), controllers, batteries and inverters. The energy produced by a generation system is distributed to the users by electric cables (distribution system). The term “microgrid” in this paper refers to the ensemble of the generation and the distribution systems. A microgrid composed by a single demand point with the generation system located in the same point is also referred to as an “independent generation point”. The radial microgrid configuration (i.e. a single generation system per microgrid and distribution in form of a tree as in Fig. 1) is considered in this study as it is the preferred one in rural electrification projects [15].

2.3 Problem statement

The aim of the AVEREMS design problem is to find the lowest cost configuration (generation points’ locations and microgrids design) that accomplish with the energy and power demands of all the users, taking into account energy resource maps and different technical constraints. A detailed description of the AVEREMS problem constraints and mathematical formulation is reported in Appendix A. Next, the objective function of the problem and the constraints of the generation and distribution systems (Fig. 1) are resumed:

- Objective function: To minimize the capital cost of the project, considering all components defined in Fig. 1, i.e. wind turbines, wind controllers, solar photo-voltaic (PV) panels, solar controllers, batteries, inverters, meters, and cables.

- Constraints of the *generation system*: In each generation point, generators, controllers, inverters and batteries must be installed in order to cover the energy and power demands of connected users. The demand of the users is estimated at the horizon time of the project to consider the possible load growth. Generators and batteries must satisfy the energy demand, while inverters must fulfill the power demand. For the dimensioning of the generators, batteries and inverters the following aspects must be also considered: energy resources available in the area, energy and power losses due to equipments’ efficiencies, the minimum days of autonomy and the maximum battery discharge factor. In particular, the required days of autonomy are set in order to take into account the uncertainty in the wind and solar resource generation (e.g. as higher the uncertainty for a certain project, higher the days of autonomy of the batteries). This feature together with the consideration of the minimum resource month and the combination of different renewable resources (hybrid systems) intrinsically takes into account the generation uncertainty and reduces the risk of lack of energy supply. Controllers are dimensioned depending directly on the installed generators. Generation systems could be located in every point of a certain area (thus not forcedly close to demand points as considered by [7]).

- Constraints of the *distribution system*: Every demand point must be connected to the generation system by an electric cable. The type of cable installed must satisfy maximum permitted voltage drop considering nominal distribution voltage, and cable resistance and maximum intensity. Microgrid structure is radial. Consumption meters must be installed in microgrids connecting multiple users.

Fig. 2 shows a solution to the AVEREMS problem in a community of 22 users distributed on an area of 1 km x 1 km. For each generation point, besides generators (indicated in Fig. 2), the number and type of the other components to be installed in the generation system, i.e. controllers, batteries and inverters (Fig. 1), must be specified. For each branch of a microgrid the type of cable must be specified in order to fulfill with distribution system constraints.

Please insert Figure 2

3. Enhanced deterministic heuristic

The deterministic heuristic proposed in [9] is considered as the starting point for the development of the proposed metaheuristic procedure. That heuristic is a fast method composed by 2 phases: first construction, and then a local optimization. In the "construction phase", the solution considering all independent generation points is firstly calculated, and then the algorithm iteratively extends microgrids as much as possible, according to the cost criterion. The "local optimization phase" is composed by 2 steps that are repeated if they improve the previously obtained solution (i.e., the solution cost is reduced): firstly the microgrids are divided into smaller ones and then the resulting microgrids are tried to be interconnected between them in a better way.

The "construction phase" in [9] has the following drawback. The microgrids are always created solving the minimum spanning tree problem [16], which, given a generation point and a set of users to connect, looks for the configuration of the distribution system that minimizes the cable length. However, this configuration does not ensure the minimum cost because it depends on both the cable length and the cable type (i.e. unitary cost) used in order to fulfil distribution system constraints, such as maximum permitted voltage drop. Thus, the cable type should also to be taken into account when deciding the distribution system.

In order to improve the original heuristic, we propose an enhanced deterministic heuristic based on the one proposed in [9]. The general scheme of the enhanced heuristic is shown in Figure 3 and the heuristic is described in the next sub-Sections. The original "construction phase" is modified in order to be easily adapted as the starting point of a meta-heuristic procedure (see Section 4). Moreover, we include an additional third phase, "distribution system optimization phase", which aims to reduce the distribution system cost. In that third phase, instead of using the minimal cable length distribution, longer lengths that may reduce the global solution cost are considered.

Sub-Section 3.1 lists and describes the internal functions used in the proposed enhanced heuristic. The description and reasoning of the "construction phase" and the "distribution system optimization phase" are presented in detail is sub-Section 3.2 and 3.3, respectively. The "local optimization phase" is equal to the one originally proposed in [9] and, therefore, it is not detailed here.

Please insert Figure 3

3.1 Internal functions

The internal functions used in the heuristic description are hereby reported. Some of these functions are defined to facilitate its posterior usage in the GRASP based algorithm described in Section 4. The functions use symbols defined in the “nomenclature” Section.

CM(*m*)	Cost of microgrid *m*, including all components of the generation and distribution systems.
CS(*s*)	Cost of solution *s*. $CS(s)=\sum_{m\in MS(s)} CM(m)$
LPA(*x*,*a*)	Minimum distance between point *x* and arch *a*
LPM(*x*,*m*)	Minimum distance between point *x* and microgrid *m* If $\lvert P(m)\rvert = 1$ then $LPM(x,m)=L(x,R(m))$ else $LPM(x,m)=\min_{a\in A(m)} LPA(x,a)$
LC(*m1*,*m2*)	Estimation of the cable extension required to connect microgrids *m1* and *m2*. $LC(m1,m2)=\delta\cdot\min\left(\min_{x\in P(m1)} LPM\left(x,m2\right),\ \min_{x\in P(m2)} LPM\left(x,m1\right)\right)$ δ is a coefficient used to take into account possible slight differences between microgrids’ distance and real cable extension. In the heuristic proposed in [9] δ=1 was assumed. In this study a value of δ=0.85 is considered in order to increase the possibility of connecting microgrids and thus to enlarge the search space of the algorithm.
BED(m)	Break Even Distance (*BED*) of microgrid *m*. It represents the maximum distance at which microgrid *m* could be reliably connected to another microgrid or to a no-demand generation point. Given *UCC* the lowest unitary cable cost [\$/m] and *CC*(*m*) the total electric cable cost of microgrid *m*, $BED(m)=\frac{CM(m)-CC(m)}{UCC}$
B(*m*)	Set of branches of microgrid *m*. A branch is defined by the arches and the points (always including the generation point) of a microgrid that are downstream the same point, i.e. the electric energy they receive pass through the same arch connecting the generation point and a child of it (see Fig. 2).
MB(*B*)	Microgrid composed by the set of braches *B*
DU(*a*,*b*)	Set of users part of branch *b* that are downstream arch *a* (the electric energy they receive pass through arch *a*)
AB(*b*)	Set of arches of branch *b* sorted in a decreasing order by *PF(a)*, i.e. the product of arch length and the power flow circulating by it. For each $a\in AB(b)$, the parameter *PF(a)* is calculated as $PF(a)=L(a)\cdot\sum_{u\in DU(a,b)} PD(u)$
CB(b)	Cost of the cables of branch *b*. Cable connections within a branch follow a radial tree-scheme and are realized so that cable length is minimized using the classical shortest connection network algorithm [16]. The cable type with the minimum cost that fulfills with the maximum permitted voltage drop and the maximum flowing intensity is selected.
BD(*a*,*b*)	Set of 2 branches {$BD_1(a,b)$, $BD_2(a,b)$} resulting from removing arch *a* of branch *b*. Branch $BD_1(a,b)$ is composed by arches connecting all users *DU(a,b)*, while branch $BD_2(a,b)$ is composed by the arches connecting the rest of users

Split(*b*) Set of (1 or 2) branches that results after trying to eliminate one by one all arches of *b*. The function stops when a division is accepted because the distribution system cost is reduced. If no division is accepted then the function returns *b*. The algorithm of this function is reported in the following.

```
For ($a \in AB(b)$)
    If $CB(BD_1(a,b)) + CB(BD_2(a,b)) < CB(b)$ then
        return $\{BD_1(a,b), BD_2(a,b)\}$
    EndIf
EndFor
return $\{b\}$
```

ImproveCableCost(m) Function that tries to divide all the branches of microgrid m into smaller ones in order to reduce the distribution system cost. For each branch the following steps are carried out:

- It calculates the cost of dividing the branch into 2 smaller ones, eliminating one arch of the branch. All the arches are tried to be eliminated.
- If the cost of the 2 new branches is lower than the initial branch cost then the sub-division is accepted. Therefore the same subdivision process is carried out for the resulting 2 branches.
- The procedure stops when no more subdivision is accepted.

Let DB be the set of branches to be divided, b be the current branch that is tried to be divided and B* be the set of least cost branches. The detailed algorithm of this function is described in the following.

```
Initialize variables: $B^* = \emptyset$; $DB = B(m)$;
While ($DB \neq \emptyset$)
    $b$ = first element of $DB$; $DB = DB \setminus \{b\}$
    If ($Split(b) = \{b\}$) then $B^* = B^* \cup \{b\}$
    else $DB = DB \cup Split(b)$
EndWhile
Return $MB(B^*)$
```

In this function the generation point of microgrid *m* does not change. Thus $R(MB(B^*)) = R(m)$.

$MR(m, x, r)$ Microgrid composed by $DP(m)$ demand points with generation in point x. Cable length is firstly minimized using the shortest connection network algorithm [16].
If r = true: Cable cost is then improved utilizing the *ImproveCableCost(m)* function.
If r = false: Cable cost is not improved.

MU(*m1*,*m2*, *r*)	Microgrid (*mu*) that results after connecting (according to Prim's algorithm [16]) all demand points of microgrids *m1* and *m2*. Therefore, $DP(mu) = DP(m1) \cup DP(m2)$ If *r* = true (cable cost is improved): The cable cost of *mu* is obtained utilizing the *ImproveCableCost(mu)* function; the root of microgrid *mu* is the one that leads to the lower cost between the root of *m1* and the root of *m2*: if *CM*(*MR*(*mu*,*R*(*m1*),true)) < *CM*(*MR*(*mu*,*R*(*m2*),true)) then *mu* = *MR*(*mu*,*R*(*m1*),true) otherwise *mu* = *MR*(*mu*,*R*(*m2*),true). If *r* = false (cable cost is not improved): *R*(*m2*) is selected as the root of *mu* only if it leads to a lower microgrid cost and has a Hybrid Potential Indicator (*HPI*) higher than *R*(*m1*): if *CM*(*MR*(*mu*,*R*(*m2*),false)) < *CM*(*MR*(*mu*,*R*(*m1*),false)) and *HPI*(*R*(*m2*)) > *HPI*(*R*(*m1*)) then *mu* = *MR*(*mu*,*R*(*m2*),false) otherwise *mu* = *MR*(*mu*,*R*(*m1*), false). *HPI*(*x*) is a resource indicator that considers the multiple renewable resources available in the area: higher the *HPI*(*x*) higher the resource(s) potential in point *x*. *HPI*(*x*) is calculated according to [17].
SelectM(*m*, *M*)	Returns the microgrid *mc* to be connected to microgrid *m*. *mc* is selected from set *M* of microgrids. The selected microgrid *mc* is $mc = \underset{z \in M \mid LC(z,m) \le max\left(BED(z),BED(m)\right)}{\arg\max} \left(\left(CM(m) + CM(z) \right) - CM\left(MU(m,z,\text{true}) \right) \right)$
IGC(*s*, *ND*)	Returns the solution with generation in the best (low cost) demand point of each microgrid or in a no-demand point of set *ND*. For every microgrid *m* of solution *s*, the point *x* (part of the microgrid *m* or of set *ND*) that, if selected as the root, leads to the minimum microgrid cost is defined as microgrid generation point. In this function, set *ND* does not include no-demand points that are already the generation point of another microgrid part of solution *s*. $IGC(s,ND) = S\left(\bigcup_{m \in MS(s)} MR\left(m, \underset{x \in P(m) \cup ND}{\text{argmin}} \left(CM\left(MR(m,x,\text{true}) \right) \right), \text{true} \right) \right)$

3.2 Construction phase

The reasoning of the construction phase is the following. First, it is considered that all demand points are independent generation points (i.e., a solution without any microgrid). This is a trivial solution that may be a high cost solution. Then, the heuristic constructs iteratively the microgrids extending them as much as possible whenever the solution cost decreases. The microgrids are subsequently constructed in the following two iterative cycles, which are shown in Fig. 4:

1) Cycle 1: New microgrid construction iteration starts. The grid generation point of the (current) microgrid is firstly selected (STEP1) and then it starts cycle 2 in which the microgrid is extended.

2) Cycle 2: In each iterative step a microgrid (composed by one or more users) is tried to be connected to the current microgrid depending on certain criterion (STEP2). If the new microgrid has a lower cost than the two previous ones then the connection is accepted and Cycle 2 restarts. If the connection is not accepted then a new Cycle 1 starts.

The algorithm ends when all the demand points of the community are part of a created microgrid, i.e. a microgrid that was already tried to be extended.

Please insert Figure 4

The “selection steps” (STEP1 and STEP2 of Fig.4) are the most critical parts of the algorithm and are defined by two characteristics: the pool of possible candidates (PE_1, PE_2, respectively) and the indicator or heuristic function (HF_1, HF_2, respectively) used to rank the set PE and select the best candidate.

Regarding STEP1, the pool of possible candidate elements (PE_1) from which the microgrid generation point could be selected is the union of the sets of demand (D) and no-demand points (ND), not selected as a grid generation point in a previous iteration of cycle 1 (equation 1). As the number of initial no-demand points in an area could be considerably high, e.g. wind generation points are generally presented in form of a wide spatial grid with a spacing of 50 or 100 m, an “initial filter”, proposed in [9], is firstly applied to pre-select most promising generation locations taking into account resource and demand distributions.

- $PE_1 = D \cup ND$ (1)

The heuristic function (HF_1) to rank the elements of the set PE_1 is the Grid Generation Score (GGS): an indicator that, based on demand and resource distributions, evaluates how much a certain point has the adequate characteristics for being the generation point of microgrid composed by multiple users (for more details see [17]). The point with the highest HF_1 (equation 2) is selected:

- $HF_1(x) = GGS(x) \quad \forall x \in PE_1$ (2)

Regarding STEP2, i.e. the selection of the microgrid to connect, being m the current microgrid in expansion, the pool of possible candidates (PE_2) is composed by all microgrids of the current solution s (excluding m) located at a distance from m lower than their Break Even Distance (BED) (equation 3).

$$PE_2 = \left\{ mc \in MS(s) \setminus \{m\} \middle| LC(mc,m) \leq BED(mc) \right\} \tag{3}$$

The microgrid y that is tried to be connected to microgrid m could be selected in the following three different ways, adapted from [11]: HF_{2a}, HF_{2b} and HF_{2c} (equations 4, 5 and 6).

1) By distance (the element with the lowest HF_{2a} value is selected):

$$HF_{2a}(y) = LC(y,m) \quad \forall y \in PE_2 \tag{4}$$

2) By *NGS*, *IGS* and distance (the element with the highest HF_{2b} value is selected):

$$HF_{2b}(y) = \frac{\max\limits_{py \in DP(y)} \left(1 + NGS(py) - IGS(py); 0.1\right)}{LC(y,m)} \qquad \forall y \in PE_2 \tag{5}$$

The *NGS* (No-generation Score) and the *IGS* (Independent Generation Score) are indicators that evaluate how much some a-priori characteristics of a point indicate that it should be a no-generation point (*NGS*) or an independent generation point (*IGS*) (for more details see [17]). As *NGS* and *IGS* can range from 0 to 2, a minimum value of the numerator is defined (0.1) in order to obtained always positive values of the HF_{2b}.

3) By savings (the element with the highest HF_{2c} value is selected):

$$HF_{2c}(y) = \left(\left(CM(m) + CM(y)\right) - CM\left(MU\left(m, y, \text{false}\right)\right)\right) \quad \forall y \in PE_2 \tag{6}$$

As the heuristic function that leads to the best results is not always the same [9], the algorithm is launched three times, each time with one of the 3 HF_2, and finally the best found solution is returned.

3.3 Distribution system optimization phase

As it has been mentioned, when constructing the microgrids, the distribution is configured only considering the minimal cable length. However, since the cable costs are not taken into account, the minimal distribution cost is not ensured. The distribution cost may be reduced utilizing less expensive cables with a non-minimal cable length configuration and thus decreasing the total distribution cost.

This reduction is the objective of the proposed “Distribution system optimization phase”, which we apply to the solution returned by the “local optimization” phase (Fig. 3). The scheme of the third phase is shown in Fig. 5: firstly the branches of the microgrids of a previously obtained solution are tried to be subdivided, i.e. “Branches subdivision” (sub-Section 3.3.1) and then obtained microgrids are iteratively tried to be interconnected, i.e. “Microgrids interconexion” (sub-Section 3.3.2).

Please insert Figure 5

3.3.1 Branches subdivision

This step aims to improve the distribution system cost of the microgrids of the current solution by means of trying to subdivide the branches. Therefore, the function “*ImproveCableCost()*” is applied to every microgrid, as shown in the following.

Parameters

is	Initial solution
*M**	Set of least cost microgrids

Algorithm

```
1. $M^* = \bigcup_{m \in MS(is)} ImproveCableCost(m)$
```

```
2. Return $S(M^*)$
```

3.3.2 Microgrids interconnection

During this step the microgrids of the current solution are tried to be interconnected. For each microgrid *m* the following sub-steps are carried out:

- The microgrids located at distance to the microgrid (*m*) lower than their Break-Even Distance are tried to be connected (separately) to *m*. Next, in order to improve the distribution system, the "*ImproveCableCost()*" function is applied to each newly obtained microgrid. The microgrid *mc* that leads to the highest savings is selected.
- If the connection between microgrids *m* and *mc* decreases the cost of the solution then the two microgrids are connected and the algorithm tries to connect another microgrid to the latter obtained microgrid.
- This process stops when the connection is rejected (no cost improvement is obtained).

A detailed description of the procedure is reported in the following. As shown in Fig. 5, this algorithm is part of an iterative process.

Parameters

is	Initial solution
IM	Set of microgrids part of the initial solution *is* sorted by the number of connected points in descending order (in case of tie, by total cable length in descending order)
ND	Set of no-demand points pre-selected by the initial filter [9] as possible generation points
RM	Set of remaining microgrids that should be tried to be interconnected with the other microgrids
m	Current microgrid that is tried to be interconnected to the other microgrids
SM	Set of remaining microgrids that could be connected to *m*
mc	Selected microgrid to be connected to *m*
s	Current solution
sn	New solution obtained
AcceptCon	Boolean variable that indicates if the connection of microgrids *m* and *mc* is accepted or not
Continue	Boolean variable value that indicates if a new connection will be tried or not
*s**	Least cost solution

Algorithm

```
1. Initialization: $RM = IM; s^* = is;$
2. While ($RM \neq \emptyset$)
3.   $m$ = first element of $RM$; $RM = RM \setminus \{m\}$; $SM = MS(s^*) \setminus \{m\};$
4.   $s = s^*;\ Continue = \exists mc \in SM \,\middle|\, LC(mc,m) \leq \max\left(BED\left(mc\right), BED(m)\right)$
5.   While ($Continue$ and $SM \neq \emptyset$)
6.     Select the microgrid to be connected to m: $mc = SelectM(m, SM)$
7.     $m = MU(m, mc, \text{true})$; $SM = SM \setminus \{mc\};\ sn = S(SM \cup \{m\})$
```

```
8.          Connection acceptance criterion: $AcceptCon = (CS(sn) < CS(s))$
9.          If ($AcceptCon$) then $s = sn$; $s^* = sn$; $RM = RM \setminus \{mc\}$; EndIf
10.         $Continue = AcceptCon$ and $\exists mc \in SM \,\middle|\, LC(mc,m) \le \max\left(BED\left(mc\right), BED(m)\right)$
11.     EndWhile
12. EndWhile
13. Improve generation cost: $s^* = IGC(s^*, ND)$
14. Return $s^*$
```

4. GRASP based algorithm

The enhanced deterministic heuristic described in Section 3 (from now on referred as the "deterministic heuristic") improves the performance of the previous deterministic heuristic proposed by [9], with a very small increase in the computational time, as verified in sub-Section 5.2. Nevertheless, when the improvement phases (second and third phases) are applied to the solution obtained in the construction phase, a local optimum is returned, which may not be the global optimal solution. Figure 6 shows a solution obtained in the construction phase (point "0"), and how it is led by the improvement phases to the basin of attraction of the valley at which point "0" belongs (a local optimum, point "1"). However, as shown in Fig. 6, the set of all possible feasible solutions is generally composed by multiple local optima [18]. Thus, it is not guaranteed the quality the solution generated by the enhanced deterministic heuristic in comparison with the global optimum.

In the last few decades, several meta-heuristic procedures have been developed in order to escape from local optima, which allows to explore better the solution space (i.e, to explore other valleys). Thus, better solutions may be found [11]. Among other metaheuristics, the Greedy Randomized Adaptive Search Procedure (GRASP) has been proposed [12]. GRASP is a multi-start metaheuristc. Specifically, GRASP generates different solutions at random (which may belong to different valleys) and improve them in order to obtain different local optima (see Fig. 6). As stopping criterion is usually defined a maximum calculation time or a maximum number of iterations. Obviously, the best local optimum found is returned.

Please insert Figure 6

GRASP has been successfully applied to many location optimization problems [13] including the capacitated plant location problem [14], which has many similarities with the AVEREMS problem (see [9]). Thus, we propose a GRASP based algorithm to solve AVEREMS.

In each iteration of the proposed GRASP algorithm, two phases are applied (Fig. 7): random solution construction and solution improvement (or local search) which starts at the constructed solution and applies iterative improvement until a local optimum is found. Repeated applications of the randomized construction procedure yields diverse starting solutions for the local search and the best overall solution obtained in the process is kept as the result.

Please insert Figure 7

In the following, we describe the new randomized solution construction (sub-Section 4.1) and the different proposed algorithm versions (sub-Section 4.2).

4.1 Randomized construction phase

The randomness of the GRASP is introduced in the solution construction phase in order to generate a wide range of different initial solutions and therefore improve the exploration of the solution space (Fig. 6). Assuming that a solution is composed by different elements that could be ranked by a heuristic function, the randomness can be introduced in the way these elements are selected [12]. As stated in sub-Section 3.2, microgrids can be seen as the different elements of a solution that are subsequently constructed in two iterative cycles (Fig. 4). Within each cycle there is a "selection step" (STEP1 and STEP2) in which the elements are ranked by a heuristic function and then the best ranked element is selected. Instead of selecting the best element, two restricted candidate lists (RCLs) could be used in STEP1 and STEP2 in order to introduce randomization:

1) *RCL1*: list for the selection of the microgrid generation point (STEP1).
2) *RCL2*: list for the selection of the microgrid that is tried to be connected (STEP2).

In the classical GRASP implementation [12], a single RCL is used. Hereby two RCLs are considered in order to increase the randomization effect, enhance the variability of the constructed solutions and thus enlarge the exploration of the solution space.

The main characteristics of the RCLs are: the pool of possible candidates, the size (nº of elements) of the RCL, the heuristic function and the selection procedure. These characteristic for RCL1 and RCL2 are reported in Table 1 and next described:

a) The pool of possible candidates for STEP1 and STEP2 (respectively PE_1 and PE_2) are defined in sub-Section 3.2 (equations 1 and 3).

b) Regarding the size, the number of best ranked elements (according to their heuristic function) to be included in the RCL could be defined as [19]:

$$SE = \max\left(\left[\alpha \cdot |PE|\right], 1\right) \text{ where } 0 \leq \alpha \leq 1 \tag{7}$$

Note that if $\alpha = 0$ then the selection is deterministic (i.e. the best ranked element is always selected), while as α increases higher will be the randomness of the selection (with $\alpha = 1$ the highest randomness is achieved). The appropriate choice of the value of parameter α is clearly critical and relevant in order to achieve a good balance between computation time and solution quality [20]. Parameter α will be calibrated for both RCL1 and RCL2 (sub-Section 5.3.1).

c) The heuristic functions (*HF*) used in STEP1 and STEP2 are defined in sub-Section 3.2. There is a single HF_1 for STEP1 (equation 2), while there are three possible HF_2 (HF_{2a}, HF_{2b}, HF_{2c}, defined in equations 4, 5 and 6) for STEP2.

d) Regarding the selection procedure, in the original GRASP the selection of an element from the RCL is done in a uniform random way: all elements of the list have the same probability to be chosen [12]. However, later studies showed that better results can be achieved by a random biased selection, in which the probability of selecting a certain element is proportional (or inversely proportional) to its heuristic function [21]. Therefore, being HF_i the value of the heuristic function for element *i*, the selection probability p_i of element *i* from a RCL is calculated as:

- Proportional selection (P): $p = \frac{HF_i}{\sum_{y \in RCL} HF_y}$ (8)
- Inversely proportional selection (IP): $p_i = \frac{1/HF_i}{\sum_{y \in RCL} 1/HF_y}$ (9)

The set *RCL* is composed by the *SE* best ranked elements of the pool of possible candidates (*PE*). Elements are sorted by their *HF* value in a decreasing or increasing order in the case of respectively proportional or inversely proportional selection.

Please insert Table 1

4.2 Different algorithm versions

As shown, there are three heuristic functions for STEP2 (HF_{2a}, HF_{2b}, and HF_{2c}). The heuristic function that obtains the best results cannot be defined a-priori. Therefore, we propose to analyze the performance of the following 5 GRASP based algorithm versions:

- GRASP1: HF_{2a} is always applied in each STEP2
- GRASP2: HF_{2b} is always applied in each STEP2
- GRASP3: HF_{2c} is always applied in each STEP2
- GRASP4: HF_{2a}, HF_{2b} or HF_{2c} are randomly selected (with the same probability) in each STEP2 of the construction phase.
- GRASP5: HF_{2a}, HF_{2b} or HF_{2c} are alternatively applied in each GRASP iteration.

Furthermore, another algorithm version (GRASP0) in which the selection of the microgrid generation point (RCL1) and the selection of the microgrid to be connected (RCL2) are totally random, i.e. $\alpha_1 = \alpha_2 = 1$ and $HF_1 = HF_2 =$ constant (e.g. 1), is also analyzed in order to evaluate the importance of utilizing good heuristic functions. The performances of these algorithm versions are compared in Section 5.

5. Computational experiment

In the previous Sections, an enhanced deterministic heuristic (Section 3) and then a GRASP based procedure (Section 4) were presented in order to support the design of autonomous community rural electrification projects based on renewable energies considering a combination of independent generation points and microgrids.

Hereby, we carried out a computational experiment in order to analyze the performance of the proposed algorithms. The analyzed instances are firstly described in sub-Section 5.1; then the improvements of the enhanced deterministic heuristic in comparison with the previous one [9] are analyzed (sub-Section 5.2); in sub-Section 5.3 the different GRASP based algorithm versions are calibrated and finally the performance of the best version is evaluated in comparison with the procedure available in literature (sub-Section 5.4). All calculations were done on a PC Intel Core 2 i7-2600 3.4 GHz with 8 GB of RAM. The code and the results obtained with the best GRASP version are available in [22].

5.1 Analyzed instances

The same instances utilized in [9] are used: the complete input data are available in [22]. The instances were randomly generated based on the characteristics of the following 5 real rural electrification projects: El Alumbre (Peru), Alto Perú (Peru), Achada Leite (Cape Verde), El Roblar (Nicaragua) and Sonzapote (Nicaragua). Real projects resource data are utilized in order to generate the instances: solar resource was estimated by NASA database [23], while the wind resource map of the area (with a grid spacing of 100 m) was obtained using a micro-scale wind flow model [5].

The electricity requirements of each user (household) are 420Wh/day and 300W of energy and power demand respectively. Regarding electrical equipments, the following data were considered:

- Wind turbines (4 types): nominal power: 100 W to 2000 W; cost (including controllers): \$1394 to \$8732.
- PV panels (3 types): nominal power: 50 W to100 W, cost: \$451 to \$821.
- PV controller (3 types): maximum power: 50 W to 100 W, cost: \$67 to \$95.
- Batteries (4 types): capacity: 1500 Wh to 3000 Wh; cost: \$225 to \$325; efficiency 85%; maximum discharge rate: 0.6; autonomy: 2 days.
- Inverters (4 types): maximum power: 300 W to 3000 W; cost: \$377 to \$2300; efficiency 85%.
- Electric cables (2 types): cost: \$4.9/m and \$5.1/m; resistance: 2.71 and 2.15 Ω/km; maximum intensity: 89 and 101 A; nominal voltage: 220 V; minimum voltage: 220 V; maximum voltage: 230 V.
- User consumption meter: cost: \$50 (installed only in microgrids composed by multiple users).

The instances have a variable number of users (ranging from 10 to 90) and, regarding users' distribution, they were randomly generated considering two different concentrations (last row of Table 2). According to the characteristics described in Table 2, two set of instances were generated: a "training set" of 90 instances for the calibration of the internal parameters used by the developed procedures and a "test set" of 450 instances for comparing the performance of the developed procedures.

Please insert Table 2

5.2 Performance of the enhanced deterministic heuristic

The solutions of the enhanced deterministic heuristic described in Section 3 ("enhanced deterministic heuristic" or "EDH") are compared with those obtained by the previous deterministic heuristic [9] ("initial deterministic heuristic" or "IDH"). The results of the comparison between the 2 algorithms in the test set of 450 instances are shown in Table 3: columns 3 to 6 show the mean solution cost ("cost") and mean computation times ("time") of the IDH and the EDH for different groups of instances; columns 7 shows the % of the difference between mean solution costs; column 8 and 9 indicate respectively the number of instances (in percentage) in which EDH improves the IDH of more than 1% and vice versa (in the rest of instances the differences between solutions of the 2 algorithms are lower than 1%).

The improvement of the enhanced heuristic is highly related with the number of users of the community (Table 3), i.e. the complexity of the instance to be solved. The effect of including the cable optimization phase is almost null for communities up to 30 users in which initial heuristic were found to be close to the optimal, according to [9]. The improvement of the EDH in comparison with the IDH increases rapidly as the number of users increases: for communities of more than 60 users significant improvements (more than 1%) of the EDH are found in 20% of the instances, whereas significant improvements of the IDH were found in less than 3% of the instances. The total mean solution costs of the IDH and the EDH are 87615$ and 87392$ respectively: the slight increase in calculation time is compensated by the solution improvement obtained by the enhanced deterministic heuristic.

Please insert Table 3

5.3 Selection of best GRASP based algorithm version

As stated in sub-Section 4.2, different algorithm versions (based on the GRASP) should be analyzed, depending on the heuristic function utilized in the selection of the microgrid that is tried to be connected. In this Section all versions are firstly calibrated (Section 5.3.1) and then performances are compared in order to select the best one (Section 5.3.2).

5.3.1 Calibration of the algorithms

As stated in sub-Section 4.2, the value of parameter α, i.e. the ratio of possible candidates included in the RCL, is highly relevant in order to achieve a good balance between computational time and solution quality of a GRASP. Therefore, the parameters $\alpha_1 = 0, 0.2, \ldots, 1$ and $\alpha_2 = 0, 0.2, \ldots, 1$ are calibrated, i.e. all combinations of values are tried, for the different algorithm versions on the "training set" of 90 instances. A computational time of 800 s is considered for each instance. The combinations of values that lead to the best (mean lowest cost) solutions are reported in Table 4.

Please insert Table 4

5.3.2 Comparison of different algorithm versions

Hereby, the 5 algorithm versions (GRASP1 to GRASP5) together with GRASP0 are compared and their results on the "test set" of 450 instances are shown in Fig. 8 and Table 5. Fig. 8 shows the convergence curves, i.e. the evolution of the cost of the best solution obtained by each version over the computational time. Each point of these curves is the mean value of the solution costs in the 450 instances at different computational times. For each GRASP version, Table 5 shows the mean solution cost obtained with 3600 s (column 2) and the percentage of instances for which each version finds a solution that is less than 1% worse than the best solution obtained by the 6 versions (column 3).

Please insert Figure 8

Please insert Table 5

The version that does not use any heuristic function (GRASP0) obtains the worst results: its mean solution cost is higher than 87000$ (while all other versions are below 86800$) and its convergence curve is always above all the others. This confirms the importance of utilizing good heuristic functions for the selection of the elements in the RCLs.

The convergence curves of the other algorithm versions (GRASP1 to GRASP5) have a similar pattern: most of the improvement is reached in the first 1000 s (dotted line in Fig. 8) whereas afterwards the curves tend to be horizontal (asymptotes). GRASP1 and GRASP2 obtain better results in comparison with GRASP3, possibly because the calculation for the savings (HF_{2c}) requires longer computational time than the other heuristic functions (HF_{2a} and HF_{2b}). However the versions that utilize the 3 heuristic functions (GRASP4 and GRASP5), taking advantage of the benefits of each one, are better options. GRASP4 (in which the HF utilized in each launch of RCL2 is randomly selected between HF_{2a}, HF_{2b} and HF_{2c}) is the best version: its convergence curve is always below all the others, its final mean solution cost is the lowest one (86666$) and it obtains the best solution in more instances (99.8%) than GRASP5 (99.1%).

Therefore, the version GRASP4 is selected as the proposed solving procedure of this study.

5.4 Performance of the GRASP based procedure

As introduced, the only known algorithm that solves the AVEREMS problem thus designing off-grid electrification projects based on renewable energies considering micro-scale resource variations, a combination of independent generation points and microgrids and generation far from demand points is the deterministic heuristic proposed by [9] (called "IDH"). A preliminary computational experiment showed that the solutions of that algorithm considerably improve the solutions obtained by other procedures that, with some limitations, deal with the same design problem: the mathematical model proposed by Ferrer-Martí et al. [7] and the VIPOR software [10]. Considering the same assumptions and set of instances used in [9], it was verified that the proposed GRASP based procedure highly enhances the solutions obtained by those procedures: mean improvements of around 7% and 6% are obtained, respectively, with the mathematical model proposed in [7] and the VIPOR software [10]. An enhanced version of the IDH (called

“EDH”) was proposed in Section 3 that improves the performance of the IDH, as shown in sub-Section 5.2.

The solutions of the proposed GRASP based procedure (“GRASP” refers to GRASP4, i.e. the best algorithm version) are now compared with the ones obtained by the enhanced deterministic heuristic (EDH). As shown in Fig. 8, the enhanced heuristic (full black circle) can rapidly obtain a good solution (29 s), slightly better than the one obtained by the GRASP (blue line) in the same computational time (the same solution is reached by the GRASP after 70 s). However, when a higher computational time is available, as it is expected when dealing with the design of a long-term project, the proposed GRASP can considerably enhance the solutions obtained by the EDH.

Table 6 presents the comparison between solutions obtained by the EDH and the GRASP (with a computational time of 3600 s) in the analyzed instances. The EDH and GRASP mean solution costs and computational times are shown in columns 3-4 and 5-6 respectively. Besides the mean difference between both solutions (column 7), the percentage of instances in which GRASP improves EDH solution of more than 1% (column 8) is presented (mention that GRASP improves EDH in all instances except one in which GRASP solution is 0.1% worse than EDH solution).

Please insert Table 6

The improvement of the GRASP in comparison with EDH depends on the number of users of the community (Fig. 9), the size of community area and the type of users’ concentration:

- As the number of users of the instance increases also the differences between EDH and GRASP increase (Fig. 9). For instance of more than 30 users GRASP enhances EDH of more than 1% in more than 20% of the instances. In instances between 70 and 90 users the mean improvement is around 1%.
- As smaller the community area higher the improvement: the lowest improvements (0.4% and 0.3% respectively) are obtained in instances C1 and C5 that where users are dispersed over widest areas (12.25 and 16 km^2 respectively), while highest improvements (1.1%) are obtained in C3 that has the smallest area of just 4 km^2.
- Higher improvements are obtained in instances with higher users’ concentration: significant enhancements (more than 1%) are obtained in respectively 22% and 33% of the instances for the low and high users’ concentration types.

Please insert Figure 9

Fig. 10 shows the computational time and the number of iterations at which the GRASP reaches the asymptote, i.e. the point at which 90% of the final improvement (after 3600 s) to EDH is obtained. The computational time before reaching the asymptote increases as the number of users increases: in instances up to 60 users the asymptote is reached in less than 600 s. However, even in instances of 90 users, 90% of the final improvement is obtained in slightly more than half of the computational time (2000s over 3600s). This indicates that a computational time of 1 hour can be considered sufficient to get the most out of the GRASP in the analyzed instances.

Regarding the number of iterations before reaching the asymptote, Fig. 10 shows that this value is not that affected by the number of users of the instances. In most cases, the asymptote is reached after between 50 and 200 iterations. Thus when applying the algorithm for the design, a maximum number of iteration can be established as a stopping criterion of the GRASP based algorithm: a value above 200 iterations seems to be adequate in order to get the most out of the algorithm.

Please insert Figure 10

In order to illustrate the type of solutions obtained, Fig. 11 shows the solution of the developed GRASP based method in a community of 88 users in Nicaragua [24]. The proposed configuration combines independent systems (P0, P1, P2 and P3) with wind (Microgrid 1) and solar (Microgrid 2 and 3) microgrids that connect concentrated groups of users taking advantage of the best wind resource area (red area). It reduces the cost of the project more than 15% in comparison with a design configuration considering all independent generation points.

Please insert Figure 11

6. Conclusions

This study presents an enhanced deterministic heuristic and a meta-heuristic procedure to design rural communities' off-grid electrification projects based on renewable energies. The proposed methods consider the design of multiple microgrids and independent users, the use of hybrid systems combining different renewable energies, micro-scale resource variations and the installation of generators far from demand points.

Firstly, some enhancements to an existing deterministic algorithm proposed in a recent publication are presented. The new procedure improves solutions obtained by the previous method with a minimal increase in computational time. Based on this new heuristic, a GRASP based method is proposed in order to escape from local optima where the deterministic heuristic can remain trapped. Different algorithm versions were calibrated and compared in order to select the best one.

The performance of the proposed algorithms was tested on 450 instances from literature, generated according to real projects, with different number of users (from 10 to 90), users' concentrations and available wind and solar resources.

The new deterministic heuristic can rapidly obtain a good solution in less than 1 minute in most analyzed instances. On the other hand, the proposed GRASP based algorithm considerably enhances solutions obtained by the deterministic heuristic with a computational time of 1 hour on a standard PC, a lapse of time generally affordable taking into account the problem to be solved. This improvement tends to increase as the number and the concentration of users increases: significant improvements (higher than 1%) were obtained in more than 30% of the instances bigger than 40 users.

The proposed algorithm is a complete design tool that can efficiently support the design of stand-alone community electrification projects requiring of low computational resources. A possible future line of research could be the explicit consideration in the model of the uncertainty in the renewable energy generation.

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Appendix A – A mathematical model to solve the AVEREMS problem

The mathematical formulation of the mathematical model presented in [7] considering wind and solar energies is hereby reported.

Data

Consumption points:

P	Number of consumption points (households, schools, health centers, community centers, etc.). These are the only points where the generators can be placed.
L_{pd}	Distance [m] between two points *p* and *d* (p= 1,…, P; d = 1,…, P).
L_{max}	Maximum allowed length of segment of a cable of the microgrid.
Q_p	Set of points to which a point *p* could be directly joined with a cable segment (p= 1,…, P): $Q_p = \left\{ d = 1,...,P : p \neq d \wedge L_{pd} \leq L_{max} \right\}$.
ED_p	Electric energy demand [Wh/day] at *p* (p = 1,…, P).
PD_p	Power demand [W] at *p* (p = 1,…, P).
CM	Cost [US$] of an electric meter.

Wind Generation:

A, NA	Types of wind turbines (a = 1,…, A) and maximum number of wind turbines that can be placed at a point, respectively.
EA_{pa},	Energy generated [Wh/day] by a wind turbine placed at point *p* of type *a* (p = 1,…, P; a = 1,…, A).
PA_a	Maximum power [W] of a wind turbine of type *a* (a = 1,…, A).
CA_a	Cost [US$] of a wind turbine of type *a* (a = 1,…, A).
R	Types of battery charge wind controllers (r = 1,…, R).

PR_r	Maximum power [W] of a battery charge wind controller of type r ($r = 1,\ldots, R$).
CR_r	Cost [US$] of a battery charge wind controller of type r ($r = 1,\ldots, R$).

PV Generation:

S, NS	Types of PV panels ($s = 1,\ldots, S$) and the maximum number of PV panels that can be placed at a point, respectively.
ES_s,	Energy generated [Wh/day] by a PV panel of type s ($s = 1,\ldots, S$).
PS_s	Maximum power [W] of a PV panel of type s ($s = 1,\ldots, S$).
CS_s	Cost [US$] of a PV panel of type s ($s = 1,\ldots, S$).
Z	Types of PV battery charge controllers ($z = 1,\ldots, Z$).
PZ_z	Maximum power [W] of a battery charge PV controller of type z ($z = 1,\ldots, Z$).
CZ_z	Cost [US$] of a battery charge PV controller of type z ($z = 1,\ldots, Z$).

Energy storage:

B	Types of batteries ($b = 1,\ldots, B$).
ηb	Efficiency of the batteries [fraction of unity].
DB	Maximum proportion of discharge admitted in the batteries.
VB	Required autonomy of the batteries [days].
EB_b	Capacity [Wh] of a battery of type b ($b = 1,\ldots, B$).
CB_b	Cost [US$] of a battery of type b ($b = 1,\ldots, B$).
I	Types of inverters ($i = 1,\ldots, I$).
ηi	Efficiency of the inverters [fraction of unity].
PI_i	Maximum power [W] of an inverter of type i ($i = 1,\ldots, I$).
CI_i	Cost [US$] of an inverter of type i ($i = 1,\ldots, I$).

Microgrid:

C	Types of microgrid cables.
RC_c	Electric resistance (feed and return) [Ω/m] of a cable of type c ($c = 1,\ldots, C$).
IC_c	Maximum intensity [A] of a cable of type c ($c = 1,\ldots, C$).
CC_c	Cost [US$/m] of a cable of type c, including the cost of the infrastructure ($c = 1,\ldots, C$).
V_N ,$V_{min,}$,V_{max}	Nominal, Minimum and Maximum voltage [v], respectively.
ηc	Efficiency of the microgrid [fraction of unity].

Variables

The model has the following variables:

- Integer non-negative variables to define the location and sizing of equipment:

xa_{pa}	Number of wind turbines of type a placed at point p ($p = 1,\ldots, P;\ a = 1,\ldots, A$).
xs_{ps}	Number of PV panels of type s placed at point p ($p = 1,\ldots, P; s = 1,\ldots, S$).
xb_{pb}	Number of batteries of the type b placed at point p ($p = 1,\ldots, P; b = 1,\ldots, B$).
xr_{pr}	Number of battery charge wind controllers of type r placed at point p ($p = 1,\ldots, P; r = 1,\ldots, R$).
xi_{pi}	Number of inverters of the type i placed at point p ($p = 1,\ldots, P; i = 1,\ldots, I$).
xz_{pz}	Number of battery charge PV controllers of type z placed at point p ($p = 1,\ldots, P; z = 1,\ldots, Z$).

- Float non-negative variables to define energy and power flows and voltage:

fe_{pd}	Flow of energy [Wh/day] between points p and d ($p=1,...,P; d \in Q_p$).
fp_{pd}	Flow of power [W] between points p and d ($p=1,...,P; d \in Q_p$).
v_p	Voltage [V] at point p ($v_p = V_{min},...,V_{max}; p=1,...,P$).

- Binary variables to define the generation points, the microgrid and the meters:

$xg_p \in \{0,1\}$	1 if some wind turbine and/or PV panel is placed at point p ($p=1,...,P$); otherwise.
$xc_{pdc} \in \{0,1\}$	1 if there is a cable of type c between the points p and d ($p=1,...,P; d \in Q_p; c=1,...,C$); 0 otherwise.
$xm_p \in \{0,1\}$	1 if an electric meter is placed at point p ($p=1,...,P$); 0 otherwise.

Objective function

The objective function (10) minimizes the capital cost; i.e., the total cost of the generation, storage and distribution equipment.

$$\begin{aligned}[MIN]Z = &\sum_{p=1}^{P}\sum_{a=1}^{A} CA_a \cdot xa_{pa} + \sum_{p=1}^{P}\sum_{s=1}^{S} CS_s \cdot xs_{ps} + \sum_{p=1}^{P}\sum_{b=1}^{B} CB_b \cdot xb_{pb} + \\ &\sum_{p=1}^{P}\sum_{d \in Q_p}\sum_{c=1}^{C} L_{pd} \cdot CC_c \cdot xc_{pdc} + \sum_{p=1}^{P}\sum_{i=1}^{I} CI_i \cdot xi_{pi} + \\ &\sum_{p=1}^{P}\sum_{r=1}^{R} CR_r \cdot xr_{pr} + \sum_{p=1}^{P}\sum_{z=1}^{Z} CZ_z \cdot xz_{pz} + \sum_{p=1}^{P} CM \cdot xm_p\end{aligned} \tag{10}$$

Constraints

Constraint (11) defines the points at which wind turbines are placed and limits the maximum number of generators at the same point; in an analogous way (12) incorporates PV panels. Constraint (13) forces xg_p to be equal to 0 if neither a wind turbine nor a PV panel is placed at point *p*. Energy and power balances and conservation are described in (14) and (15), respectively. Constraint (16) establishes the capacity of the batteries. Constraints (17) and (18) relate the energy and power flows respectively, to the existence of a cable between two points. The radial distribution of the microgrid is established in (19), constraint (20) limits the voltage drops and (21) the maximum intensity. The power of battery charge wind controllers is defined in (22). In a similar way, the power of battery charge solar controllers is defined depending on the power of the corresponding PV panel (23). Inverters can only be placed at points where wind-PV generators are placed (24). Constraints (25) and (26) force the installation of electric meters at the consumption points fed by a microgrid.

$$\sum_{a=1}^{A} xa_{pa} \le NA \cdot xg_p \qquad p=1,...,P \tag{11}$$

$$\sum_{s=1}^{S} xs_{ps} \le NS \cdot xg_p \qquad p=1,...,P \tag{12}$$

$$\sum_{a=1}^{A} xa_{pa} + \sum_{s=1}^{S} xs_{ps} \geq xg_{p} \qquad p=1,\dots,P \tag{13}$$

$$\sum_{q=1|p\in Q_q}^{P} fe_{qp} + \sum_{a=1}^{A} EA_{pa}\cdot xa_{pa} + \sum_{s=1}^{S} ES_{s}\cdot xs_{ps} \geq \frac{ED_p}{\eta b\cdot \eta i}\left(\frac{1}{\eta c}+\left(1-\frac{1}{\eta c}\right)xg_{p}\right)+\sum_{d\in Q_p} fe_{pd} \qquad p=1,..,P \tag{14}$$

$$\sum_{q=1|p\in Q_q}^{P} fp_{qp} + \sum_{i=1}^{I} PI_{i}\cdot xi_{pi} \geq PD_{p}\left(\frac{1}{\eta c}+\left(1-\frac{1}{\eta c}\right)xg_{p}\right)+\sum_{d\in Q_p} fp_{pd} \qquad p=1,\dots,P \tag{15}$$

$$\sum_{b=1}^{B} EB_{b}\cdot xb_{pb} + \left(\frac{VB}{DB}\sum_{j=1}^{P}\frac{ED_j}{\eta b\cdot\eta i\cdot\eta c}\right)\left(1-xg_{p}\right) \geq \frac{VB}{DB}\left(\sum_{d\in Q_p} fe_{pd}+ED_{p}\right) \qquad p=1,\dots,P \tag{16}$$

$$fe_{pd} \leq \left(\sum_{j=1}^{P}\frac{ED_j}{\eta b\cdot\eta i\cdot\eta c}\right)\sum_{c=1}^{C} xc_{pdc} \qquad p=1,\dots,P; d\in Q_p \tag{17}$$

$$fp_{pd} \leq \left(\sum_{j=1}^{P}\frac{PD_j}{\eta c}\right)\sum_{c=1}^{C} xc_{pdc} \qquad p=1,\dots,P; d\in Q_p \tag{18}$$

$$\sum_{q=1|p\in Q_q}^{P}\sum_{c=1}^{C} xc_{qpc} + xg_{p} \leq 1 \qquad p=1,\dots,P \tag{19}$$

$$v_p - v_d \geq \frac{L_{pd}\cdot RC_c\cdot fp_{pd}}{V_n} - \left(V_{max}-V_{min}\right)(1-xc_{pdc}) \qquad p=1,\dots,P; d\in Q_p; c=1,\dots,C \tag{20}$$

$$\frac{fp_{pd}}{V_n} - \left(\sum_{j=1}^{P}\frac{PD_j}{V_{min}\cdot\eta c}\right)(1-xc_{pdc}) \leq IC_{c} \qquad p=1,\dots,P; d\in Q_p; c=1,\dots,C \tag{21}$$

$$\sum_{r=1}^{R} PR_{r}\cdot xr_{pr} \geq \sum_{a=1}^{A} PA_{a}\cdot xa_{pa} \qquad p=1,\dots,P \tag{22}$$

$$\sum_{z=1}^{Z} PZ_{z}\cdot xz_{pz} \geq \sum_{s=1}^{S} PS_{s}\cdot xs_{ps} \qquad p=1,\dots,P \tag{23}$$

$$xi_{pi} \leq NI\cdot xg_{p} \qquad p=1,\dots,P; i=1,\dots,I \tag{24}$$

$$\sum_{d\in Q_p}\sum_{c=1}^{C} xc_{pdc} \leq (P-1)\, xm_{p} \qquad p=1,\dots,P \tag{25}$$

$$\sum_{q=1|p\in Q_q}^{P}\sum_{c=1}^{C} xc_{qpc} \leq xm_{p} \qquad p=1,\dots,P \tag{26}$$

Figure 1

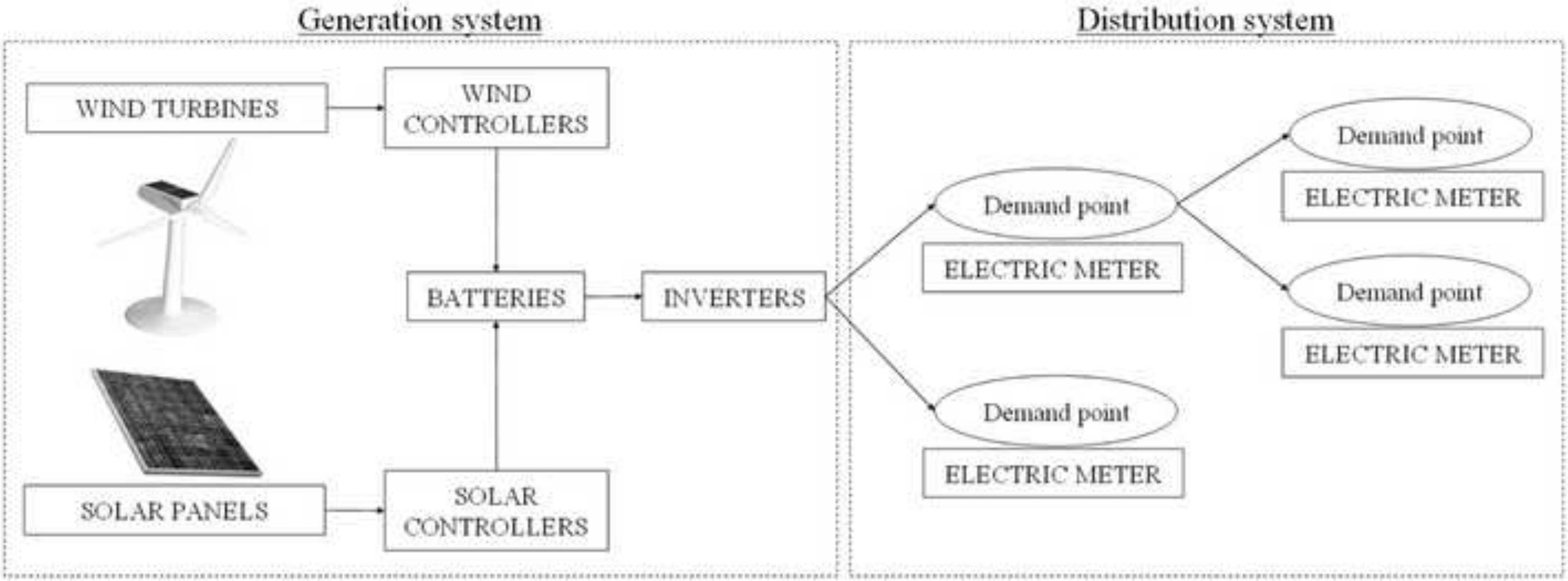

Generation system
Distribution system
WIND TURBINES
WIND CONTROLLERS
BATTERIES
INVERTERS
SOLAR PANELS
SOLAR CONTROLLERS
Demand point
ELECTRIC METER
Demand point
ELECTRIC METER
Demand point
ELECTRIC METER
Demand point
ELECTRIC METER

Figure 2

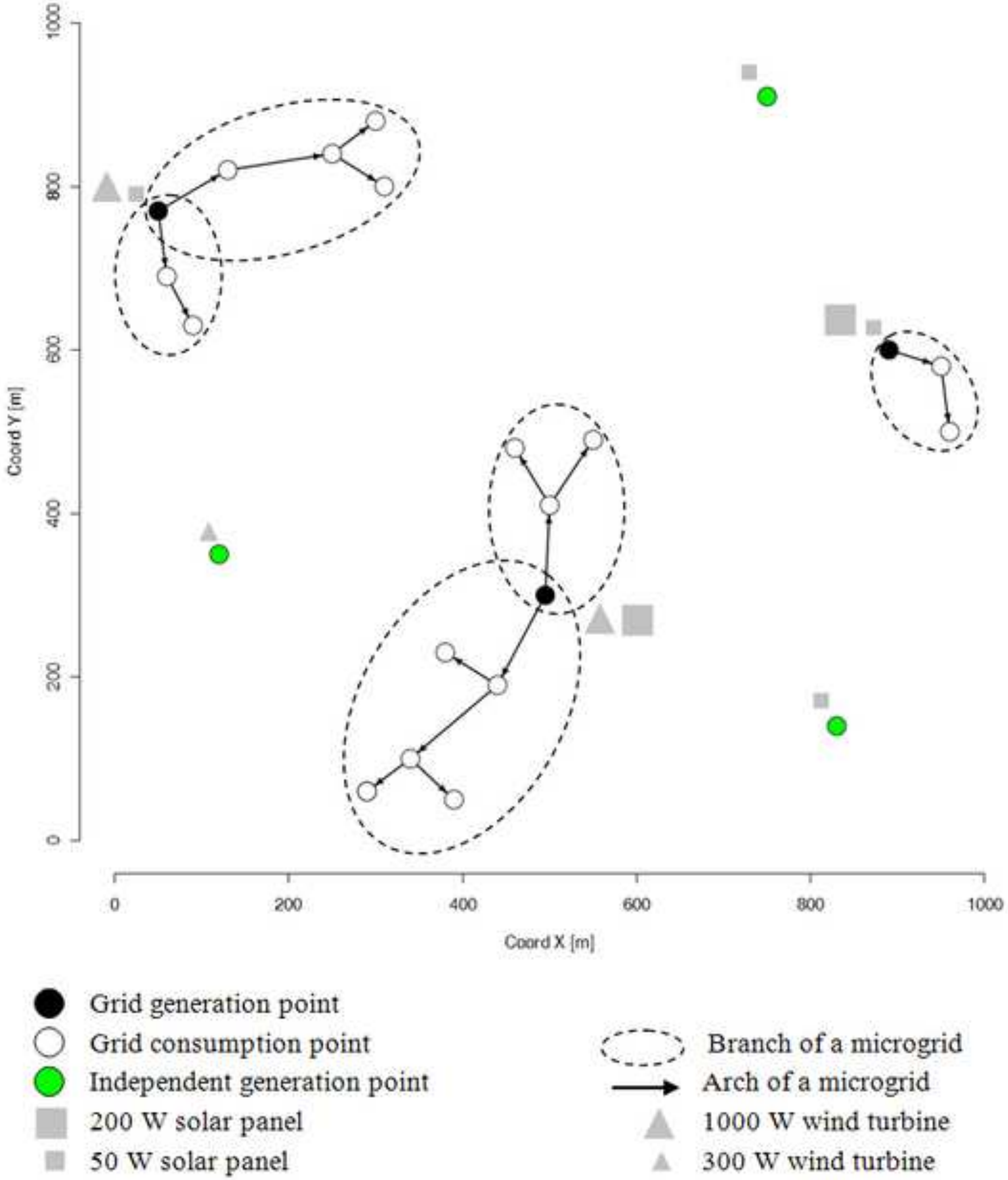

Coord Y [m]
0
200
400
600
800
1000
Coord X [m]
0
200
400
600
800
1000
Grid generation point
Grid consumption point
Independent generation point
200 W solar panel
50 W solar panel
Branch of a microgrid
Arch of a microgrid
1000 W wind turbine
300 W wind turbine

Figure 3

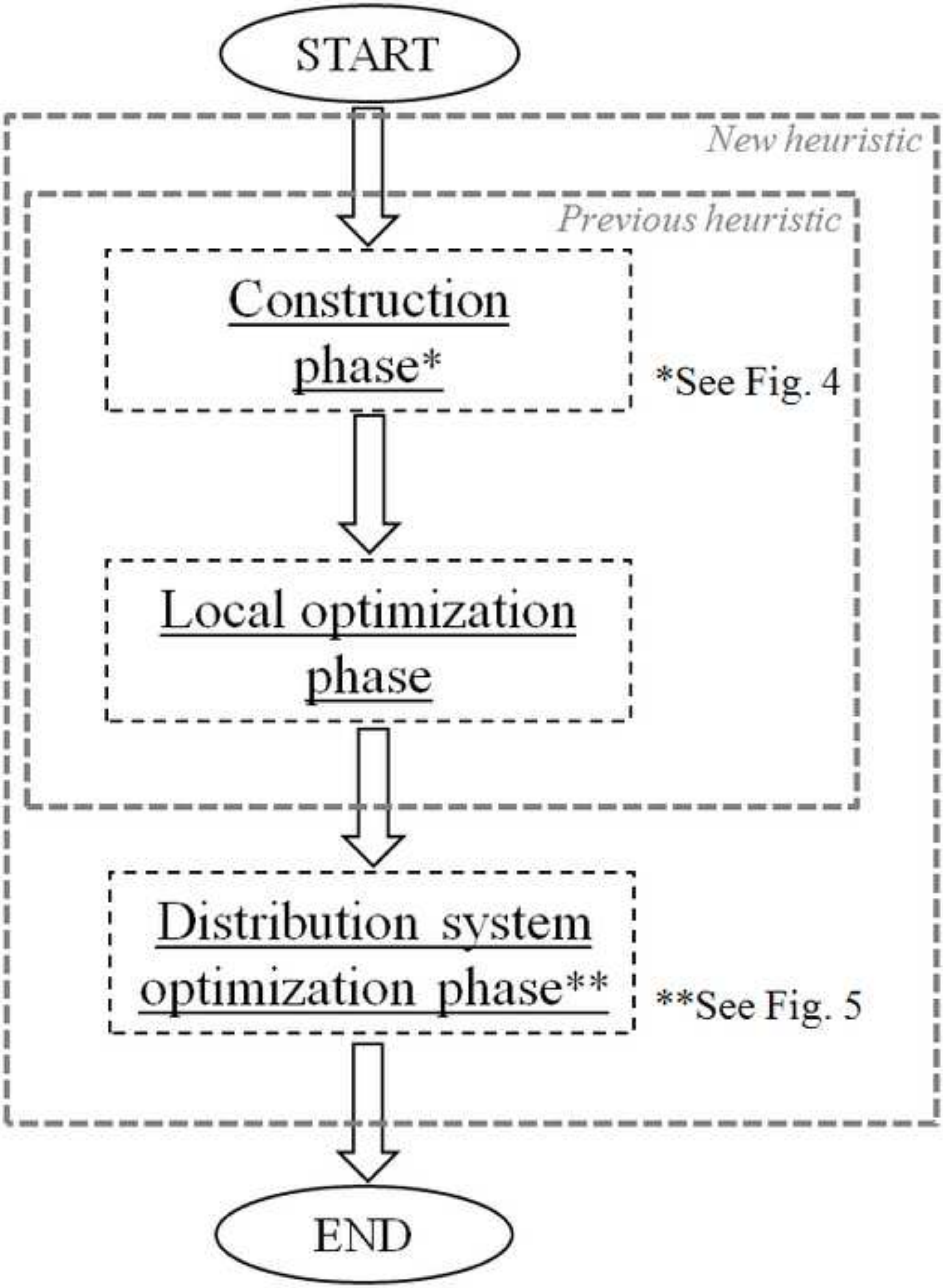
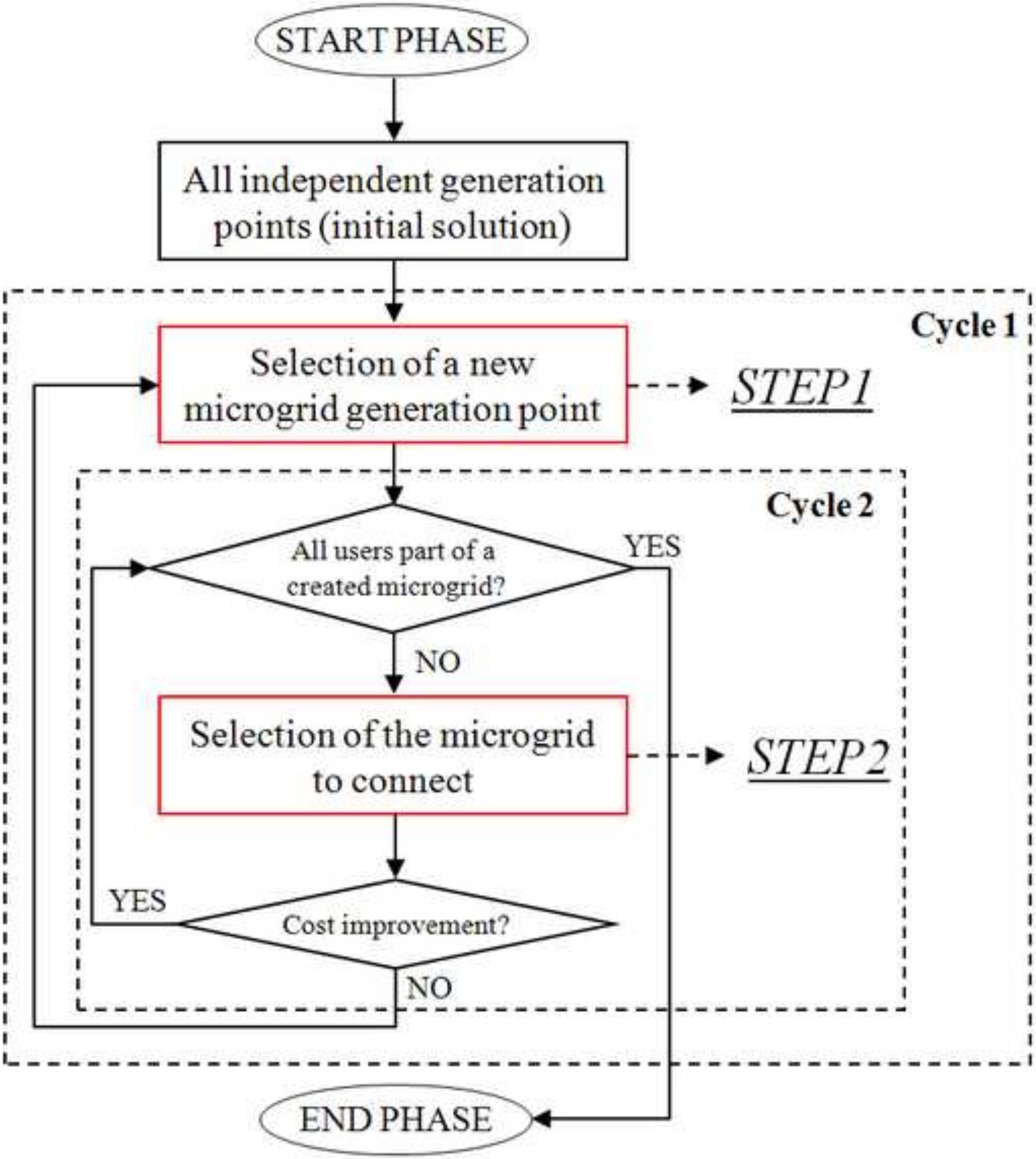

START
New heuristic
Previous heuristic
Construction phase*
*See Fig. 4
Local optimization phase
Distribution system optimization phase**
**See Fig. 5
END

Figure 4


START PHASE
All independent generation points (initial solution)
Cycle 1
Selection of a new microgrid generation point
STEP1
Cycle 2
All users part of a created microgrid?
YES
NO
Selection of the microgrid to connect
STEP2
YES
Cost improvement?
NO
END PHASE

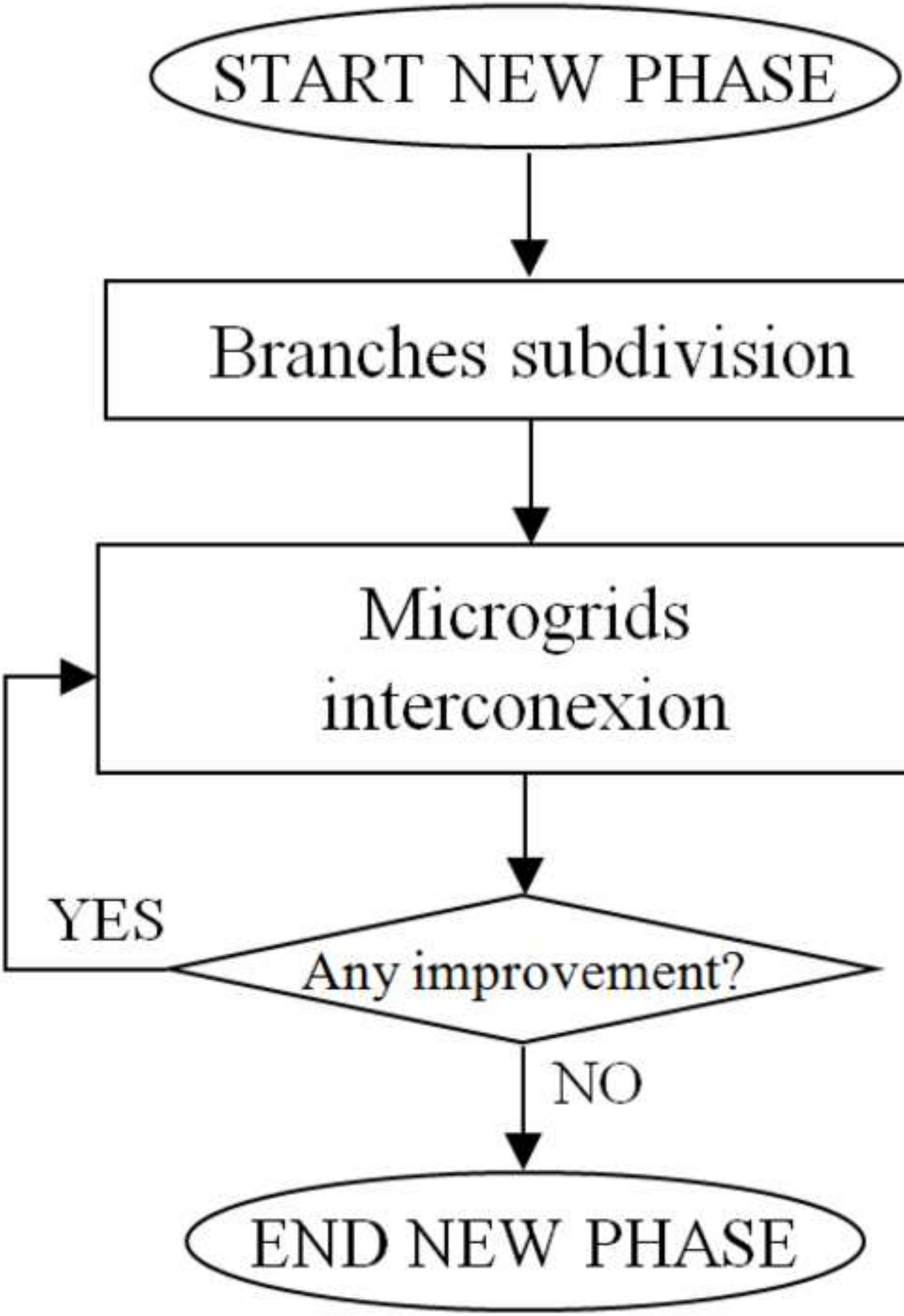

START NEW PHASE
Branches subdivision
Microgrids interconexion
Any improvement?
YES
NO
END NEW PHASE

Figure 6

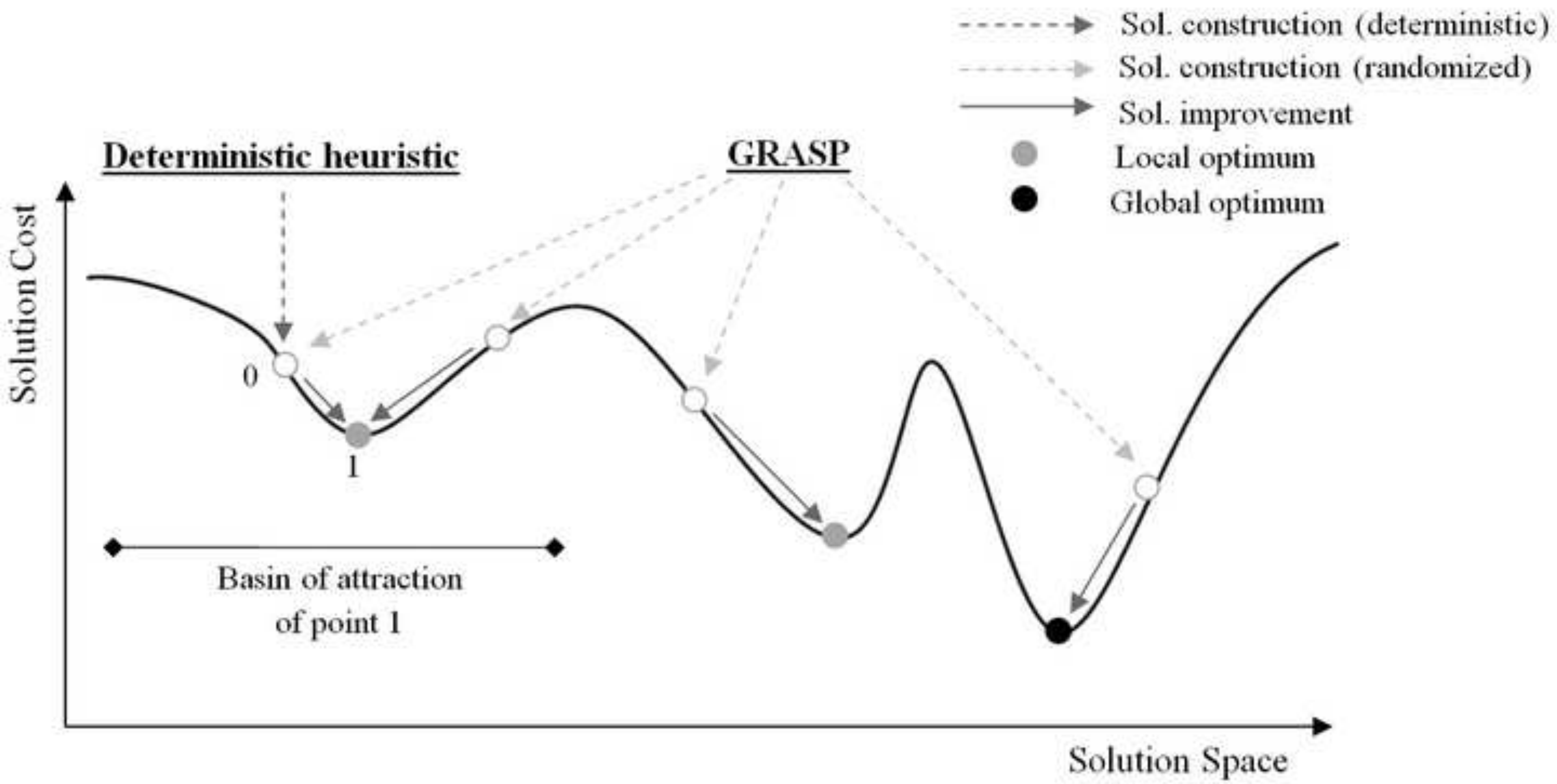

Sol. construction (deterministic)
Sol. construction (randomized)
Sol. improvement
Local optimum
Global optimum
Deterministic heuristic
GRASP
Solution Cost
0
1
Basin of attraction of point 1
Solution Space

Figure 7

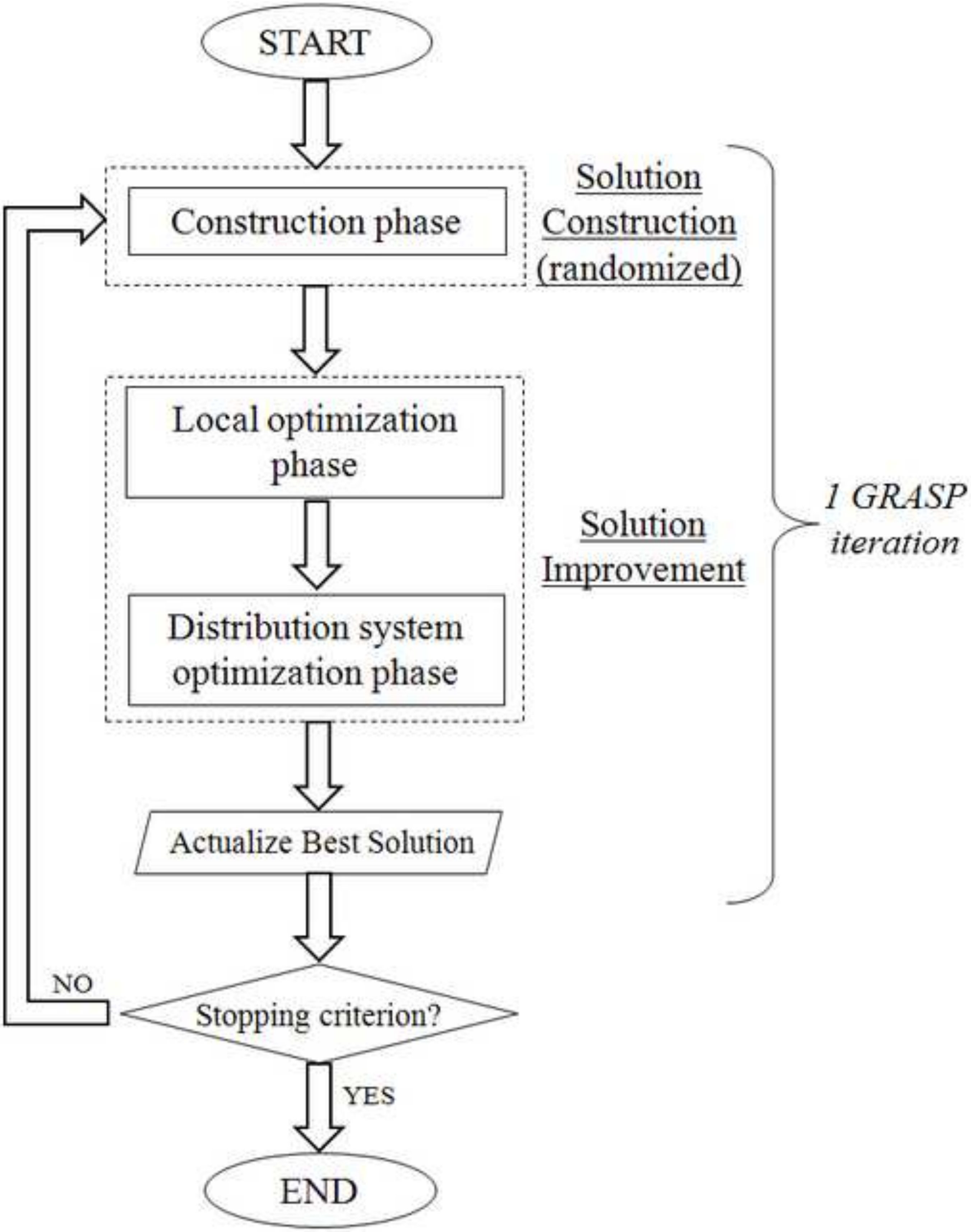

START
Construction phase
Solution
Construction
(randomized)
Local optimization
phase
Distribution system
optimization phase
Solution
Improvement
1 GRASP
iteration
Actualize Best Solution
NO
Stopping criterion?
YES
END

Figure 8

Click here to download high resolution image

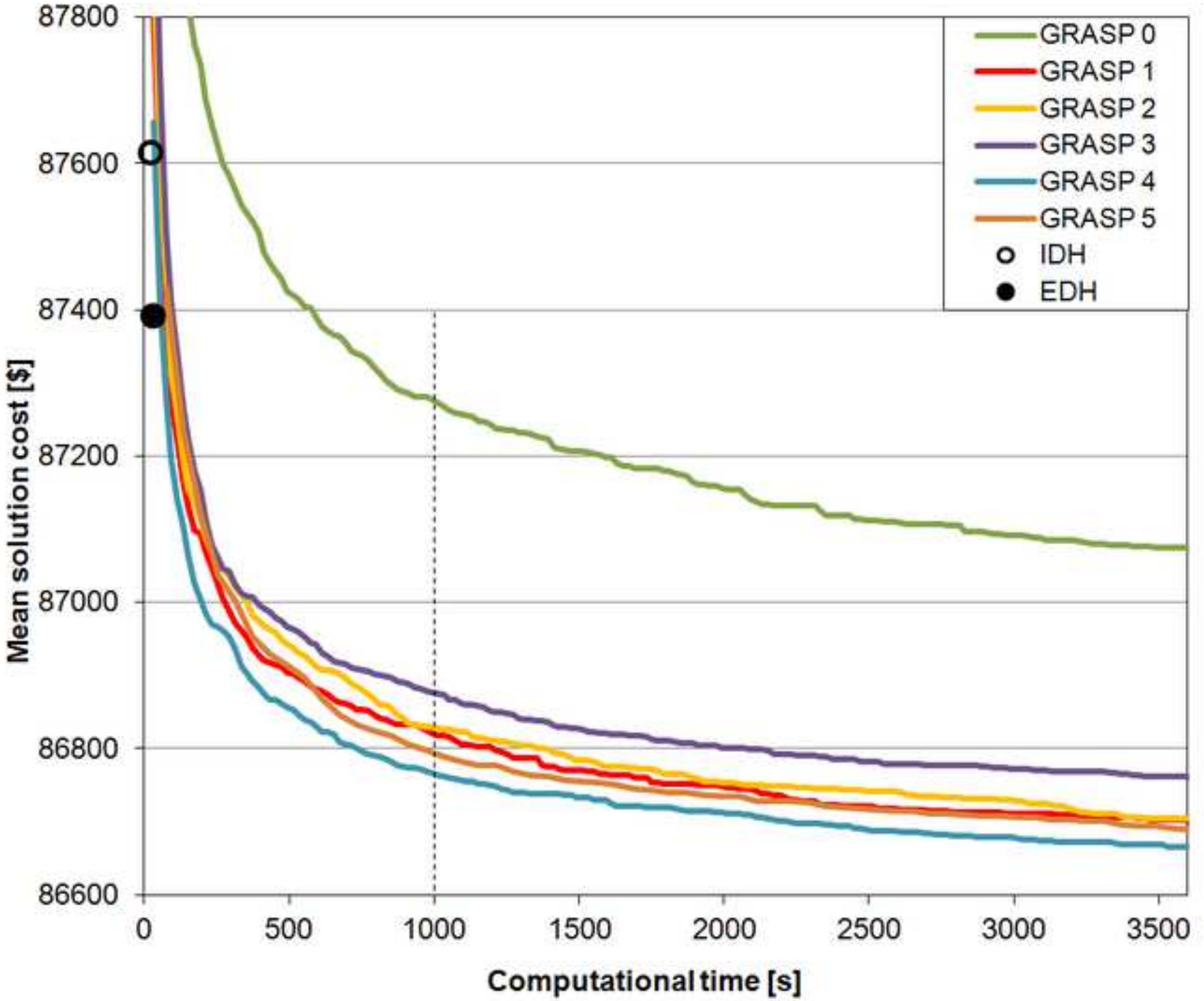


Figure 9

Click here to download high resolution image

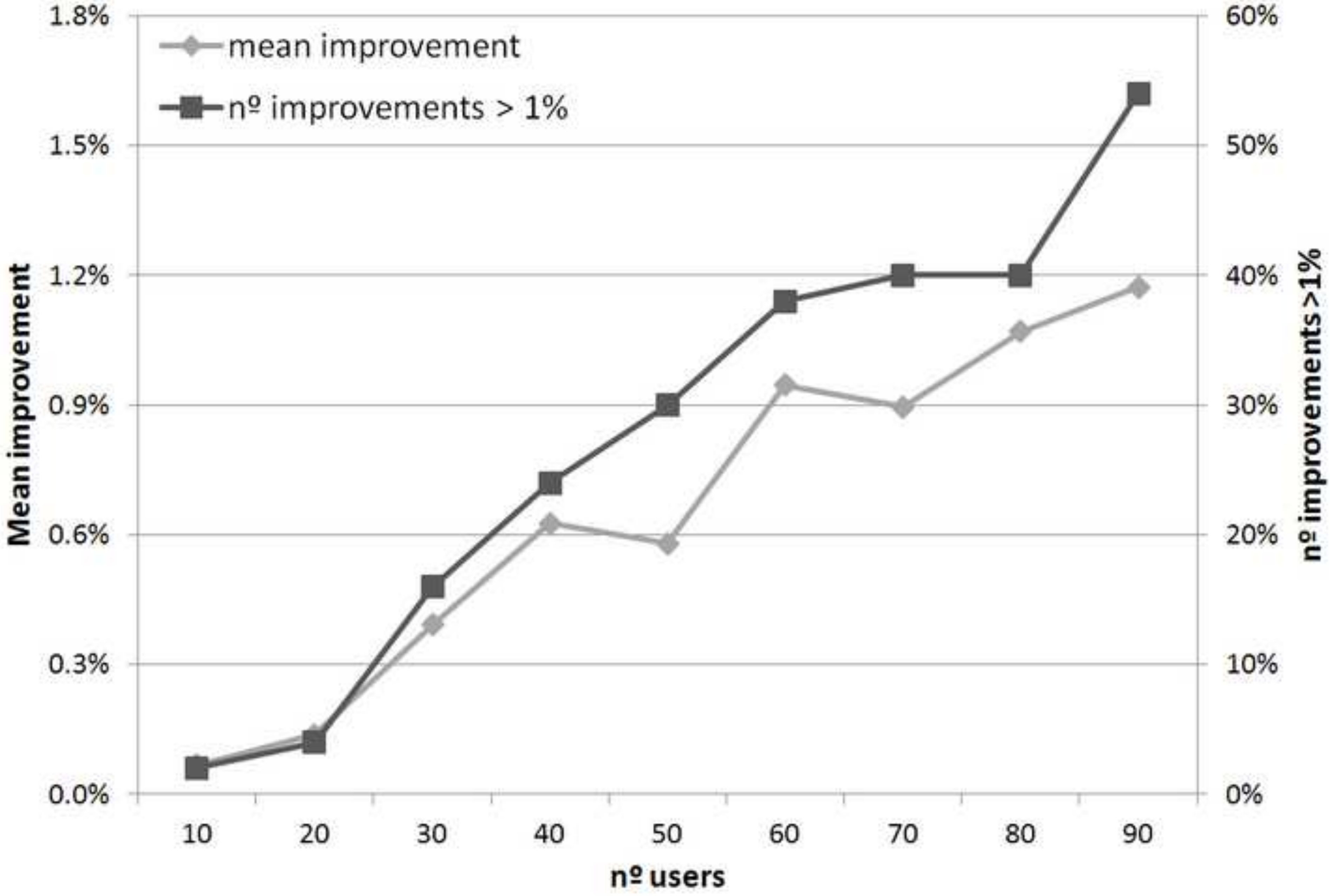


Figure 10

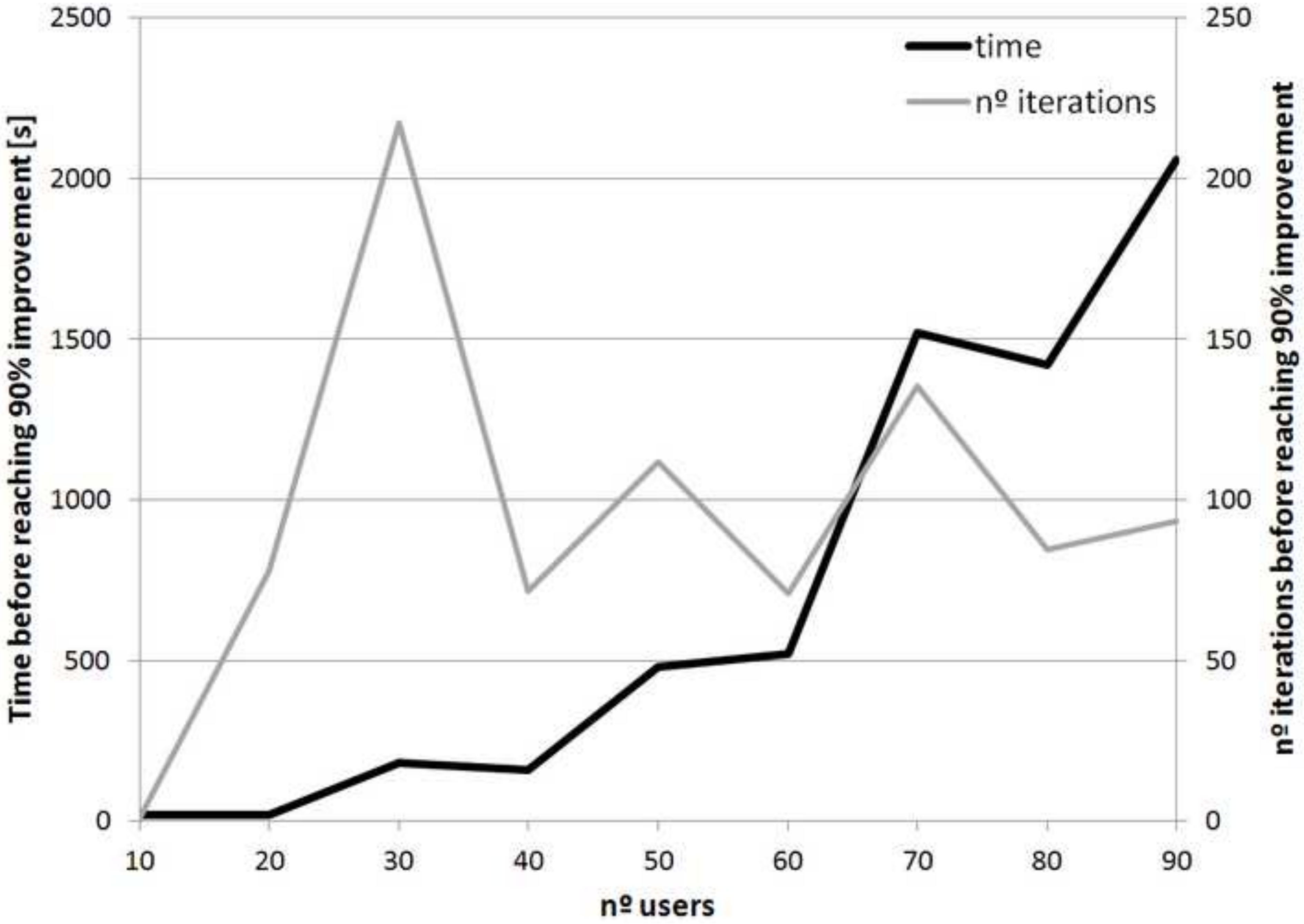
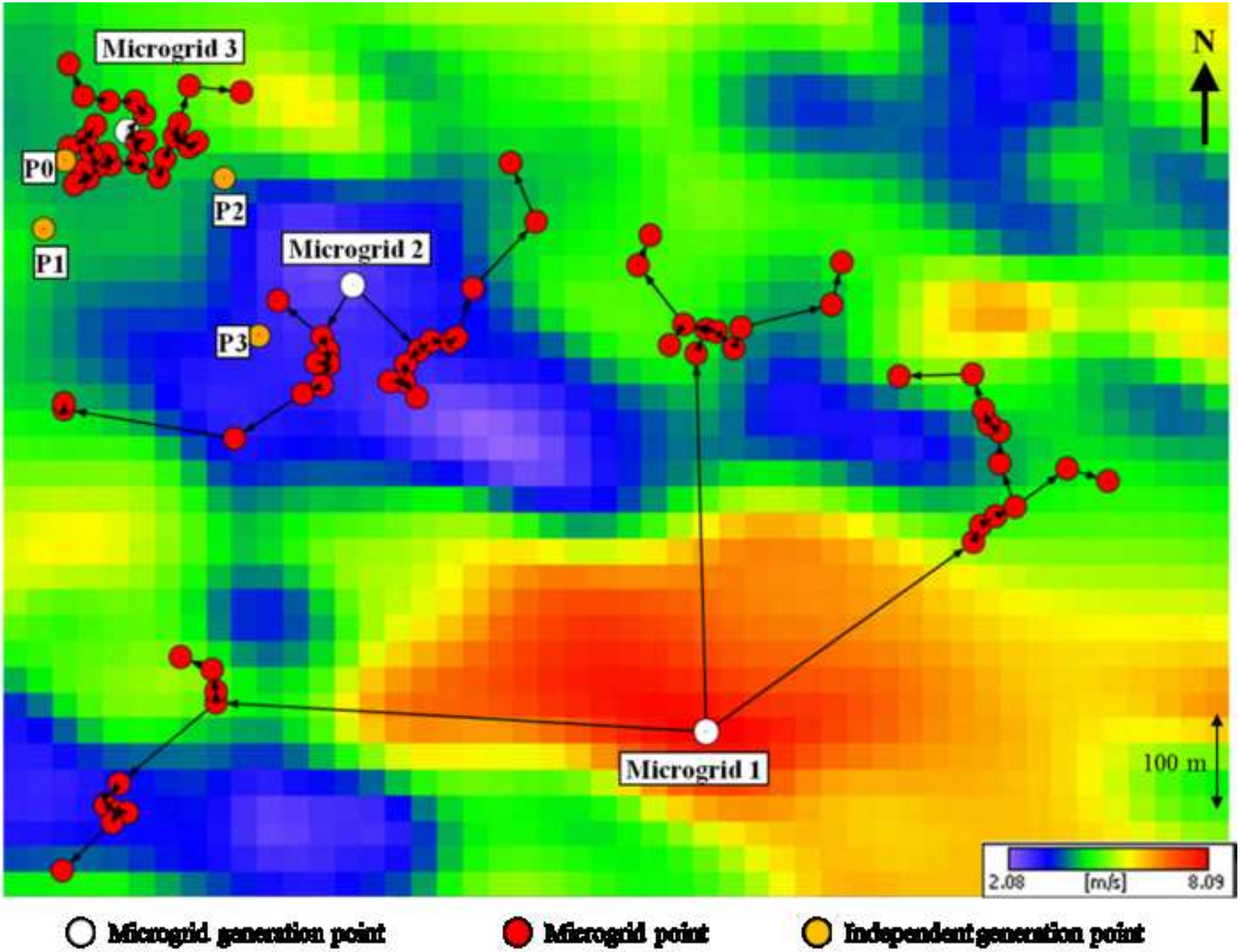

2500
2000
1500
1000
500
0
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90
time
nº iterations
Time before reaching 90% improvement [s]
nº iterations before reaching 90% improvement
nº users

Figure 11


Microgrid 3
P0
P2
P1
Microgrid 2
P3
N
Microgrid 1
100 m
2.08
[m/s]
8.09
Microgrid generation point
Microgrid point
Independent generation point

Journal name: Energy

Manuscript title: A meta-heuristic method to design off-grid community electrification projects with renewable energies

Figure Captions

Fig. 1 – Components of an off-grid hybrid wind-photovoltaic electrification system

Fig. 2 – Example of a solution to the AVEREMS problem in a community composed by 22 users

Fig. 3 – Main structure of the enhanced deterministic algorithm

Fig. 4 – Main structure of the construction phase. STEP1 and STEP2 indicate the selection steps.

Fig. 5 – Main structure of the distribution system optimization phase

Fig. 6 – Main stages of the deterministic and GRASP algorithms in the solution space of a minimization problem.

Fig. 7 – Main structure of the GRASP based algorithm

Fig. 8 – Comparison between convergence curves of the different GRASP versions

Fig. 9 – Improvement of GRASP in comparison to EDH

Fig. 10 – Computational time and nº of iterations after which GRASP reaches the 90% improvements in comparison to EDH

Fig. 11 – The obtained solution in the community of Sonzapote (Nicaragua) [24] with the mean wind speed at 10 m above ground level

Journal name: Energy

Manuscript title: A meta-heuristic method to design off-grid community electrification projects with renewable energies

Tables

Table 1 – Characteristics of RCL1 and RCL2

Characteristic	RCL1 (STEP1)	RCL2 (STEP2)
Elements of the RCL	Grid generation points	Microgrids
a) Pool of possible candidates[a]	PE_1: Set of demand and no-demand points not previously selected as a grid generation point	PE_2: Set of microgrids (excluding the current microgrid in expansion) located at a distance lower than their BED
b) Size of the RCL[b]	$SE_1 = \max\left(\left\lceil \alpha_1 \cdot \lvert PE_1 \rvert \right\rceil, 1\right)$	$SE_2 = \max\left(\left\lceil \alpha_2 \cdot \lvert PE_2 \rvert \right\rceil, 1\right)$
c) Heuristic function[a] / d) Selection procedure[c]	HF_1 / P	3 alternatives: HF_{2a} / IP HF_{2b} / P HF_{2c} / P

[a] The formal definition of PE_1, PE_2, HF_1, HF_{2a}, HF_{2b}, and HF_{2c} is reported in equations (1) to (6).

[b] The value of parameters α_1 and α_2 is calibrated in sub-Section 5.3.1.

[c] Regarding selection procedure, P and IP refer respectively to proportional and inversely proportional selection.

Table 2 – Characteristics of the analyzed instances

Type of real project	Community	El Alumbre	Alto Perú	Achada Leite	El Roblar	Sonzapote
	Project name	C1	C2	C3	C4	C5
	Area [km^2]	3.5 x 3.5	1.5 x 3.5	2 x 2	3 x 3	4 x 4
	Solar Resource [Peak sun hours]	4.3	4.3	4.8	4.2	4.3
	Wind speed [m/s]: min and max values of the map	2 – 6.5	1.5 – 4	1.1 – 7.5	1 – 10.2	0.9 – 9.7
Nº of users		10, 20, 30, 40, 50, 60, 70 80, 90				
Concentration of users		Low (25% of the users in 20% of the area) High (50% of the users in 20% of the area)				

Table 3 – Comparison between the initial (IDH) and the enhanced (EDH) deterministic heuristic

		IDH		EDH		Comparison		
		Cost [US$]	Time [s]	Cost [US$]	Time [s]	Difference	EDH > 1%	IDH > 1%
Project type	C1	89508	23.4	89426	28.8	0.06%	5.6%	3.3%
	C2	97943	29.4	97908	34.3	0.03%	4.4%	2.2%
	C3	82258	14.4	81470	23.7	0.74%	28.9%	4.4%
	C4	84670	19.3	84543	25.3	0.07%	5.6%	2.2%
	C5	83695	29.8	83615	33.5	0.02%	5.6%	3.3%
N^o of users	10-30	37747	5.0	37744	5.3	0.01%	1.3%	1.3%
	40-60	88492	19.9	88345	23.4	0.14%	8.7%	5.3%
	70-90	136605	44.9	136089	58.7	0.40%	20.0%	2.7%
Users concentration	low	88590	22.8	88381	28.2	0.17%	8.4%	0.9%
	high	86640	23.7	86403	30.1	0.19%	11.6%	5.3%
Total		87615	23.3	87392	29.1	0.18%	10%	3.1%

Table 4 – Different GRASP versions with calibrated values of α1 and α2

Algorithm version	Selection of the microgrid generation point (RCL1)		Selection of the microgrid that is tried to be connected (RCL2)	
	HF_1	α_1	HF_2	α_2
GRASP1	HF_1	0.2	HF_{2a}	0.6
GRASP2	HF_1	0.6	HF_{2b}	0.8
GRASP3	HF_1	0.6	HF_{2c}	0.2
GRASP4	HF_1	1	Randomly selected by HF_{2a}, HF_{2b}, HF_{2c}	0.2
GRASP5	HF_1	[a]	HF_{2a}, HF_{2b}, HF_{2c} are alternatively utilized	[a]

[a] As GRASP5 consists in alternatively implementing one iteration of GRASP1, one of GRASP2 and one of GRASP3, the same α_1 and α_2 values of these GRASP versions are considered for GRASP5.

Table 5 – Comparison between solutions obtained by the different algorithm versions

Version	Mean solution cost [$]	Best solution (within 1%)
GRASP0	87073	87.3%
GRASP1	86700	98.9%
GRASP2	86703	98.4%
GRASP3	86760	97.1%
GRASP4	86666	99.8%
GRASP5	86689	99.1%

Table 6 – Comparison between EDH and GRASP procedures

		EDH		GRASP		Comparison	
		Cost [US$]	Time [s]	Cost [US$]	Time [s]	Difference	GRASP > 1%
Project type	C1	89426	28.8	88989	3600	0.4%	13.3%
	C2	97908	34.3	96990	3600	0.7%	37.8%
	C3	81470	23.7	80280	3600	1.1%	45.6%
	C4	84543	25.3	83767	3600	0.7%	30.0%
	C5	83615	33.5	83302	3600	0.3%	11.1%
N^o of users	10-30	37744	5.3	37651	3600	0.2%	7.3%
	40-60	88345	23.4	87697	3600	0.7%	30.7%
	70-90	136089	58.7	134649	3600	1.0%	44.7%
Users concentration	low	88381	28.2	87787	3600	0.5%	22.2%
	high	86403	30.1	85545	3600	0.8%	32.9%
Total		87392	29.1	86666	3600	0.65%	27.6%