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ABSTRACT. *Energy transition requires a holistic approach, involving land, resources, environmental and economical data and constraints. The core purpose of energy transition, is to migrate power systems towards renewable energy usage (solar, hydro, biomass, wind), in a technical and economical viable manner. In this article we address this challenge as a spatio-temporal analysis problem combined with decision support targeted for policy makers and investors. We show how the selection of potential PV sites, can efficiently be combined with the optimization of the connection to the grid in terms of operational costs. Our contribution lies in bringing forward a modeling analogy with the SONET problem, addressed in fiber network designs. Improved results compared to an existing GIS-optimization PV site placement approach are illustrated on a real case study and data from the French Guiana.*

RÉSUMÉ. *La transition énergétique nécessite une approche holistique, impliquant la gestion des sols, ressources potentielles, les données et contraintes environnementales et économiques. L'objectif central est de migrer les systèmes électriques vers l'utilisation des énergies renouvelables (solaire, hydroélectrique, biomasse, éolienne), de manière techniquement et économiquement viable. Dans cet article, nous abordons ce défi comme un problème d'analyse spatio-temporelle intégré à un modèle d'aide à la décision conçu pour les décideurs politiques et les investisseurs. Nous montrons comment la recherche de sites photovoltaïques peut être combinée efficacement avec l'optimisation du raccordement au réseau en termes de coûts. Notre contribution réside dans la mise en place d'une analogie de modélisation avec le problème SONET, défini dans les conceptions de réseaux de fibre optique. La qualité des résultats comparés à une approche existante de placement de parcs photovoltaïques est présentée sur un cas d'étude en Guyane française.*

KEYWORDS: *Energy planning, Spatial Decision support, Spatio-temporal data*

MOTS-CLÉS : *transition énergétique, aide à la décision spatiale, données spatio-temporelles*

SAGEO'2021 - La Rochelle, 5-7 mai 2021

1 Introduction

Nowadays, the main goal of most countries' energy planning policy (Hache, Palle, 2019) in terms of *energy transition*, relies on the integration of renewable-based generation in power networks. However, increasing the share of renewable energy (RE) sources is still challenging, as a result of their inherent intermittent and geographical dispersion (Hache, Palle, 2019). Specific planning strategies (Gorsevski *et al.*, 2013; Ramirez Camargo, Stoeglehner, 2018) must be developed accordingly, in order to reach energy transition targets without threatening the existing infrastructures.

Recent works propose an integrated model framework, combining Geographic Information Systems and Robust Optimization, such as the GREECE-OPSPV (*Geographical REnewable Energy Candidate Extraction - Optimal Planning and Sizing of PV parks*) system (Al-Kurdi *et al.*, 2019; Pillot *et al.*, 2020). It identifies the optimal sites for solar photovoltaic (PV) generation at utility scale, according to specific energy planning targets. The approach connects both geographical information system (GIS) and robust linear optimization (RO) through the pipe depicted in Figure 1. The GIS component gathers large heterogeneous sets of spatiotemporal data, and allows for location and size of the best solar PV sites to be retrieved with respect to geographical constraints (restricted areas, land use, distance to grid, etc.), spatial dispersion of the resource, hourly global energy demand and generation, predefined planning scenarios, and the degree of risk adversity authorized by the decision maker. Through a set of spatio-temporal data layers and control parameters, the GIS module (GREECE) converts spatial constraints and parcels into *items* characterized by *de-spatialized* attributes and solar resource time series. Based on current electricity generation and demand time series as well as projection scenarios, the RO model (OPSPV) then looks for optimal site candidates (location, size and power), with respect to given temporal constraints (parcel size, hourly electricity demand, maximum penetration of intermittent RE power) and objectives (maximize energy generation and minimize total costs). The model eventually gives an estimate of the risk associated with solar PV investment at utility scale to the decision and policy maker, by means of a Pareto approach (cost vs. energy generation) and according to best and worst case scenarios.

In this integrated GIS and decision support model, when a solar PV site (location and size) is proposed, a new substation is considered for connection to the power network. This approach was justified as the model was designed for private investors in RE plants, thus each solar PV site required its own connection to the grid. However, in island networks (i.e. not interconnected), the network manager might have the authority to decide which site should be turned on and off, depending on the share of intermittent power (Notton

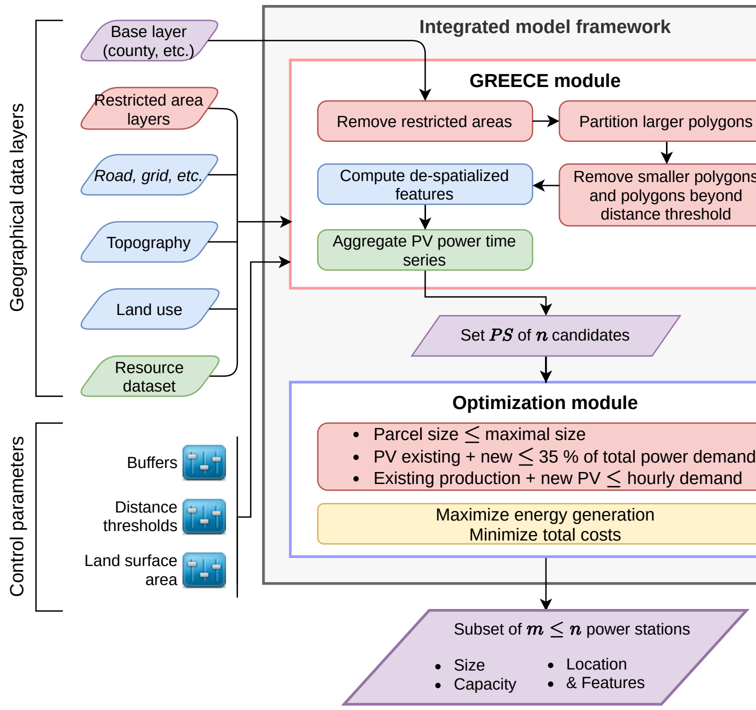


Figure 1. Schematic view of the original GREECE-OPSPV integrated model framework (Al-Kurdi et al.*, 2019)*

et al., n.d.; Tapachès *et al.*, 2019). Accordingly, some investors have moved on to diversifying their RE investments (hydro, biomass, etc.) or exploiting power plants with added storage capacity (Spaes, 2019; Tapachès *et al.*, 2019). Another solution though is to rely on co-investment, whereby several sites belonging to multiple investors would be connected to the same substation. To our knowledge this approach hasn't been investigated in terms of simulation models. This would be a cost-effective solution as the maximum power per RE site is constrained by the technical features of the power network. In fact, for multiple small-scale solar PV facilities, the final cost would grow with the number of corresponding substations. In this paper we address this problem by deriving a model that would mitigate the cost by aggregating various power plants around one unique substation. This objective comes with new challenges on the GIS and optimization model.

The problem tackled is to maximize PV energy supply and minimizing costs through small-scale power facilities. Our new framework is based on an analogy with the Synchronous Optical NETwork (SONET) (Pelleau *et al.*, 2009; Goldschmidt *et al.*, 2003), which is a popular network design in the field of fiber-optic technology. Typically, we first tailor the constraints of the SONET optimization problem to our own problem and then integrate them into the RO model of the framework. Since this raises the computational complexity of the combinatorial optimization, the data range of those constraints is first pruned by enhancing the GREECE model with respect to the spatial constraints that apply to the potential sites. It ensures keeping the CPU time reasonably low without loss of solution quality. With the proposed architecture, the best solar PV sites are now gathered into *rings*, i.e. local aggregates of plants, connected to one sole substation. It results in lower energy unit cost (M€/GWh) as well as means for the decision makers and grid managers to manage their risk adversity, compared to the previous architecture.

To describe the resulting benefits, we compare both approaches, with and without considering constraints from the SONET problem, by applying the GREECE-OPSPV framework to the real case of French Guiana. The article is structured as follows: section 2 presents the revisited version of GREECE-OPSPV based on the SONET analogy; section 3 is the experimental section based on a real-world case study and compare both results from the former and the new version of GREECE-OPSPV; section 5 concludes the paper.

2 Applying the SONET design to RE sources in power systems

2.1 Planning small-scale PV sites for safer grid operation and improved risk management

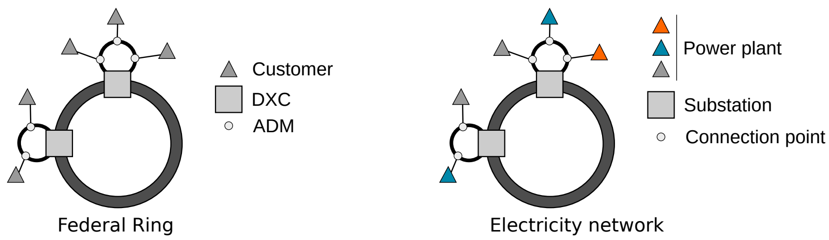
Safer grid operation. When too much intermittent power is injected into the grid, it might be necessary for the network manager to disconnect some of the solar PV sites (Tapachès *et al.*, 2019; Notton *et al.*, n.d.). When there are only large power plants, the loss of one of them could affect grid stability. The use of smaller facilities therefore gives more flexibility when handling the energy supplied from intermittent sources, and eventually ensures safer grid operation once solar PV sites have been commissioned. This idea of targeting smaller solar PV sites is even more relevant in small not interconnected electricity networks, whose low *inertia* actually implies higher impact from intermittent RE sources on frequency variability and grid stability (Notton *et al.*, n.d.; Tapachès *et al.*, 2019). Typically, the GREECE-OPSPV model allows risk adversity to be assessed *upstream* using Pareto optimisation through best and worst case scenarios (Al-Kurdi *et al.*, 2019; Pillot *et al.*, 2020). In this paper, we consider smaller PV sites, and look for handling the risk *downstream*: whether the riskier solution is chosen or not, the grid manager must remain capable of eventually switching off a plant without jeopardizing the whole network.

Risk adversity management. When there is one unique investor deploying multiple sites, it is also more interesting to invest in various small-scale facilities rather than in few bigger ones. As a matter of fact, the grid manager will not care about the economical risk but rather about the technical risk: he will eventually shut down any solar PV site in case of too much intermittent power injected into the network (Notton *et al.*, n.d.; Tapachès *et al.*, 2019). This technical liability might not be related to technical constraints, as this is the case for EDF in French Guiana which disconnects plants in the chronological order of their connection to the grid (CTG, 2017; EDF, 2019). As a result, while the investor may ensure for instance to still have 6 or 7 out of 8 small-scale PV plants running when some sites are eventually disconnected, he could loose half of the production if he only runs two large-scale facilities. This is an economical risk that some investors might not be willing to take.

Clusters of RE sources: towards the SONET analogy. Previous works on the GREECE-OPSPV model, sought each solar PV power plant to be built along its own substation (Al-Kurdi *et al.*, 2019; Pillot *et al.*, 2020). As mentioned, this approximation is no longer valid when the number of sites dramatically increases, which is the case if we only allow small-scale plants to be eventually built. In order to keep the solutions economically relevant, we revisit this model so that several power plants might actually be connected to the same substation. We present the underlying methodology in the following section.

2.2 Adapting SONET constraints to the RE planning problem

In the field of fiber-optic technology, one of the most popular network designs is the Synchronous Optical NETwork (SONET) (Pelleau *et al.*, 2009; Goldschmidt *et al.*, 2003). In one possible topology, each customer is connected to exactly one *local ring* through add-drop multiplexers (ADM), and those local rings are all connected to one *federal ring* through a digital cross connector (DXC) (Pelleau *et al.*, 2009). This topology is depicted in Figure 2a. The cost



(a) SONET with DXC (b) Power network analogy

Figure 2. Fiber optical rings (Pelleau et al.*, 2009) and power network analogy*

of DXCs is much higher than that of ADMs, so the number of DXCs must be minimized, that is the number of rings. This is known as the *SONET Ring Assignment Problem* (SRAP) *with capacity constraints.* This can be formally depicted as a node-partitioning problem for a given graph G (Goldschmidt *et al.*, 2003). Nodes of G stand for the customers to be connected and the edge weights represent the traffic demand between sites. The analogy with power networks is depicted in Figure 2b and can be summarized as follows: we may think of the federal ring as the electricity network and of the DXCs as the different substations connected to it. Various power plants can then be connected to each substation/local ring with respect to the available hosting capacity. Those power plants can be of different type, such as dispatchable (biomass, hydroelectricity, geothermal, etc.) and non-dispatchable (solar, wind, etc.) RE sources for example. Each ring may be seen as an aggregate of power plants that are spatially *close* enough to each other to be connected to the same substation.

We now show how constraints for this problem can be derived and adapted from the SRAP (Goldschmidt *et al.*, 2003), as well as developed to answer specific needs. In order to avoid combinatorial explosion, the spatio-temporal GIS model is used to determine pairwise distance between all solar PV potential sites belonging to the set PS. For each ring k, we will therefore limit the available sites to the set B_k, that is the set of site indices for which sites PS_j have distance d_{kj} from site PS_k below a threshold D (including PS_k):

$$B_k = \{j \mid j \in N = \{1, \ldots, n\}, d_{kj} \leqslant D\} \quad \forall k \in N = \{1, \ldots, n\} \tag{1}$$

We then apply the constraints from the SONET problem to revisit the former optimisation problem (see Table 1 for the nomenclature): >

$$\max_{<} \quad b \qquad \sum_k \sum_i \sum_h SA_{ik} \times Ppv_{h,i} \tag{2a}$$

$$\text{s.t.} \quad \sum_{i \in B_k} SA_{ik} \times Pnom \leqslant C \quad \forall k \in N = \{1, \ldots, n\}, \tag{2b}$$

$$\sum_k x_{ik} \leqslant 1 \quad \forall i \in N = \{1, \ldots, n\}, \tag{2c}$$

$$\sum_{i \in B_k} x_{ik} \leqslant M \times y_k \quad \forall k \in N = \{1, \ldots, n\}, \tag{2d}$$

$$M \times \sum_{i \in B_k} x_{ik} \geqslant y_k \quad \forall k \in N = \{1, \ldots, n\}, \tag{2e}$$

$$\sum_{i \in B_k} \sum_k SA_{ik} \times Ppv_{h,i} + Eint_h \leqslant 0.35 \times Dem_h \quad \forall h, \tag{2f}$$

$$\sum_{i \in B_k} \sum_k SA_{ik} \times Ppv_{h,i} + Eint_h + Ep_h \leqslant Dem_h \quad \forall h, \tag{2g}$$

$$SA_{ik} \leqslant Smax_i \times x_{ik}, \forall i \in B_k, \forall k \in N = \{1, \ldots, n\}, \tag{2h}$$

$$x_{ik} \times Smin \leqslant SA_{ik}, \forall i \in B_k, \forall k \in N = \{1, \ldots, n\}, \tag{2i}$$

$$x_{ik}, y_k \in \{0, 1\}.$$

Let $x_{ik} = 1$ if site PS_i is selected and belongs to ring k and $x_{ik} = 0$ otherwise. Let $y_k = 1$ if power plants are connected to ring k (i.e. ring is active) and $y_k = 0$ otherwise. Aggregate of PV power per ring is kept below a threshold C corresponding to the substation maximum hosting capacity (2b). Constraint (2c) ensures that a selected site only belongs to one ring. Constraints (2d) and (2e) guarantee that a ring with one or more selected PV sites is active. Constraint (2f) prevents the amount of intermittent energy from being over 35 % of the total forecast energy demand (CTG, 2017; EDF, 2017).

Satisfaction of the forecast energy demand is defined by constraint (2g), using existing resources augmented with new PV generation. Constraints (2h) and (2i) relate the size of the PV sites, lying between $Smin$ and $Smax_i$, to whether they are selected or not. This relationship is required to link both the energy production and the different costs. If a plant size is not null then the site is selected, and conversely if a site is not selected then its size is forced to be null.

Essentially the strategic energy planning over some given time horizon has two main objective functions: 1) to maximize the total hourly energy production over the year through new PV energy generation (2a), 2) to minimize the total costs related to PV installation, connection to the grid, etc. Since these functions are in different units they are not combined into a single weighted function that would not be meaningful, but instead solved by seeking the Pareto frontier, i.e. optimizing each function while constraining the other one. As a result, the optimization problem (2a)-(2i) is applied for every given constrained cost value in the range of the Pareto.

Minimize costs: Modeling non-linear functions. The total cost $Cost$ corresponds to the sum of the costs in every ring k. Each cost in ring k is the aggregate of the capital cost Cap_k of all the PV sites built in the ring, plus the connection cost to the grid $Ccon_k$, the substation cost $Csta_k$ and the operational & maintenance costs Cop_k:

$$Cost = \sum_k Cap_k + Cop_k + Ccon_k + Csta_k \tag{3}$$

Table 1. Nomenclature for the OPSPV problem formulation

$h \in H = \{1, \dots, 8760\}$	Hour (per year)
$i \in N = \{1, \dots, n\}$	Site index
$k \in N = \{1, \dots, n\}$	Ring index
n	Number of candidate sites derived from GREECE
$x_{ik},\ \ y_k$	Boolean decision variables
B_k	Boundary set of nearest PV sites corresponding to ring k
C	Substation maximum hosting capacity (kW)
M	Big number to enforce Boolean inference
$Eint_h$	Current hourly production from intermittent energy sources (kWh)
Ep_h	Current hourly production from dispatchable energy sources (kWh)
Dem_h	Estimated global (forecasted) hourly power demand (kWh)
$Pnom$	Nominal power per unit area (kW/m^2)
SA_{ik}	Surface area of new selected PV site belonging to ring k (m^2)
$Smin,\ \ Smax_i$	Minimum and maximum *area* for each candidate parcel (m^2)
PS_i	Potential Site
$Ppv_{h,i}$	Estimated *hourly production* per PV unit (kWh/m^2)
dg_i	Minimal distance from the grid to PV site centroid (m)
d_{ij}	Distance between site PS_i and site PS_j
$Clan$	Transmission line unit cost (€/m)
$Ccap_k$	Capital cost of implementation of new PV power plants (€)
Cop_k	Annual operational cost per PV power plant (€)
$Ccon_k$	Connection costs for each ring, transmission lines (€)
$Csta_k$	Capital cost for new substation per ring (€)

Capital cost Cap_k and operational & maintenance costs Cop_k are defined as piecewise linear functions (Pillot *et al.*, 2020), and depend on the nominal power range of the PV sites implemented in ring k. Regarding connection costs $Ccon_k$, using the centroid of all sites as the connection bridge to the sites would in fact make the problem nonlinear. To keep linearity, we have thus considered in first approximation the maximum distance to the grid among PV sites implemented in ring k:

$$Ccon_k = Clan \times \max_{i \in B_k}(dg_i \times x_{ik}) \quad \forall k \tag{4}$$

where $Clan$ stands for the unit cost of transmission lines (€/km). Finally, following the same idea as for the plant capital cost, we also define the substation cost $Csta_k$ as a piecewise function. The piecewise model allows for the problem to remain linear and for economies of scale in building substations to be included into the analysis. The substation cost depends on the aggregated PV nominal power in ring k, which actually determines the final substation hosting capacity:

$$Csta_k = \begin{cases} a_4 \times Pnom \times (\sum_{i \in B_k} SA_{ik}) + y_4 & \text{if } 0_{MW} \leq (\sum_{i \in B_k} SA_{ik}) \times Pnom \leq 10_{MW} \\ a_5 \times Pnom \times (\sum_{i \in B_k} SA_{ik}) + y_5 & \text{if } 10_{MW} \leq (\sum_{i \in B_k} SA_{ik}) \times Pnom \leq 50_{MW} \\ a_6 \times Pnom \times (\sum_{i \in B_k} SA_{ik}) + y_6 & \text{if } 50_{MW} \leq (\sum_{i \in B_k} SA_{ik}) \times Pnom \end{cases} \tag{5}$$

3 Case study: *ring* vs. *site* approach in French Guiana

In this section, we compare the SONET-based *ring approach* with the *site approach* (Al-Kurdi *et al.*, 2019; Pillot *et al.*, 2020). We have applied both methods in French Guiana, according to characteristics and policy targets for the horizon 2030 in the region. In the context of the French *Energy Transition Act*, it is expected to triple RE source capacities by 2023 (CTG, 2017), first by increasing solar PV, then biomass.

3.1 Data and processing

The spatio-temporal GIS GREECE model first extracts the potential sites that will feed the OPSPV module depending on geographical constraints and land management. The model prunes the unrestricted territory in order to finally get suitable parcels with respect to minimum and maximum surface area. We refer the reader to (Pillot *et al.*, 2020) for further details about the methodology. It resulted in a set PS of 133 land parcels between 1.5 and 50 ha, depicted in Figure 3. They correspond to all the potential sites where solar PV plants could be built, such that all the constraints hold. We will rely on those plots to compare both ring and site approaches.

Beyond geographic location, each potential site generated by GREECE also comes along with specific features and resource time series (e.g. solar irradiation). Those features are extracted from heterogeneous data layers and remote sensing data. Essentially, GREECE allows for *de-spatialization* and discretiza-

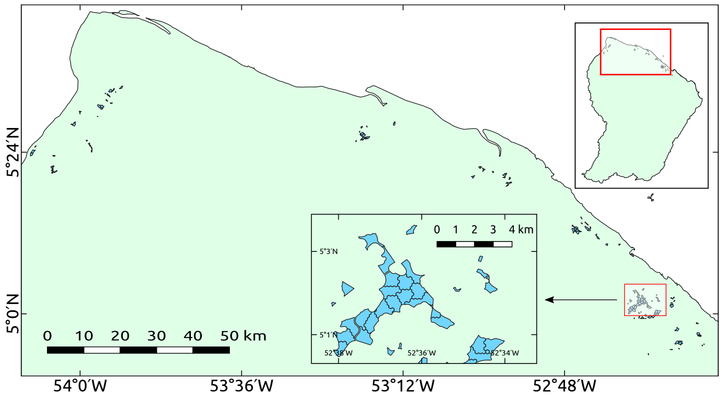


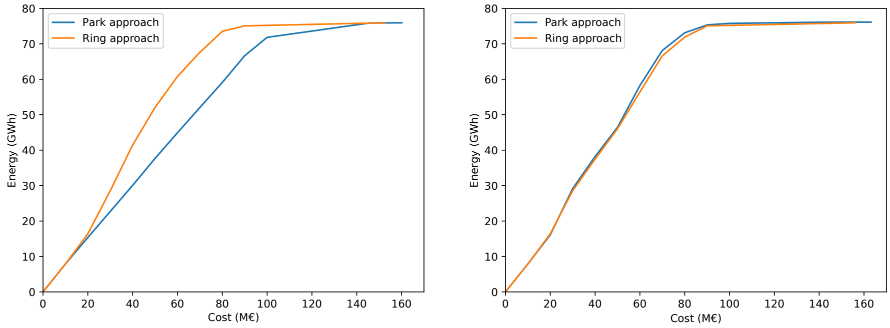
Figure 3. Set of potential sites derived by the GREECE model in Fr. Guiana.

tion of the potential sites in order to feed the combinatorial optimization model with *items* defined as tuples of digitalized attributes. In the present study, for simplicity purposes, items have been defined as tuples of 3 attributes: land surface area, distance to the grid, and time series of solar irradiation values. Our optimization model then converts those values into maximum nominal power, connection costs, and solar PV plant output power profiles.

Finally, hourly energy demand for the 2030 horizon has been projected according to 2016 records (EDF, 2019) and EDF estimations for worst case (5% annual growth) and best case (2% annual growth).

3.2 Results and analysis

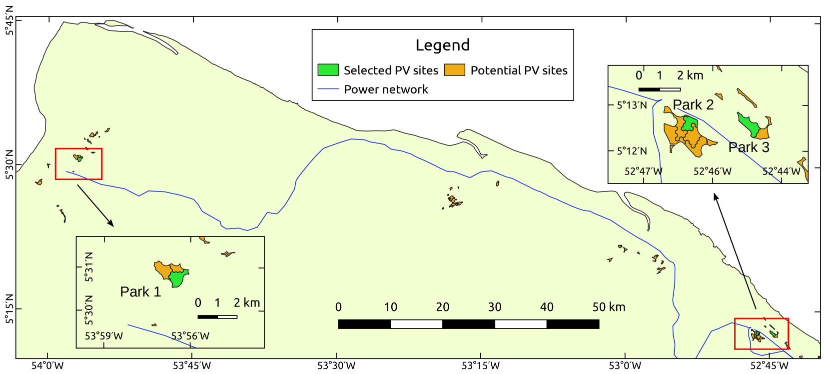
In this paper, we compare two main aspects of relevance to the decision maker and network manager (power plant energy investors in French Guiana and EDF) between the GREECE-OPSPV model (*site approach*) and our proposed SONET-based model (*ring approach*). These aspects are related to what we previously stated as safer grid operations and better risk adversity management (see section 2.1). The comparison is based on the worst case scenario implemented in the site approach. In all cases, we only consider rings made of small-scale facilities whose nominal power is not greater than 5 MW. We first compare Pareto solutions for both approaches (Figure 4) in two fair distinct cases: (a) only small-scale facilities up to 5 MW can be built in the site approach, while no limitation is set on the ring hosting capacity (i.e maximum power that can be injected into the corresponding substation, sum of all PV sites' power attached to that ring); (b) solar PV sites up to 20 MW can be built in the site approach, and so the same applies to ring hosting capacity in the ring approach, which cannot exceed 20 MW as well. The 20 MW limit corresponds to the specific technical constraints of the French Guiana power network (CTG, 2017; EDF, 2017). This comparison investigates the relative contribution of each approach with respect to economical benefits, and risk management in terms of spatial distribution of the sites.



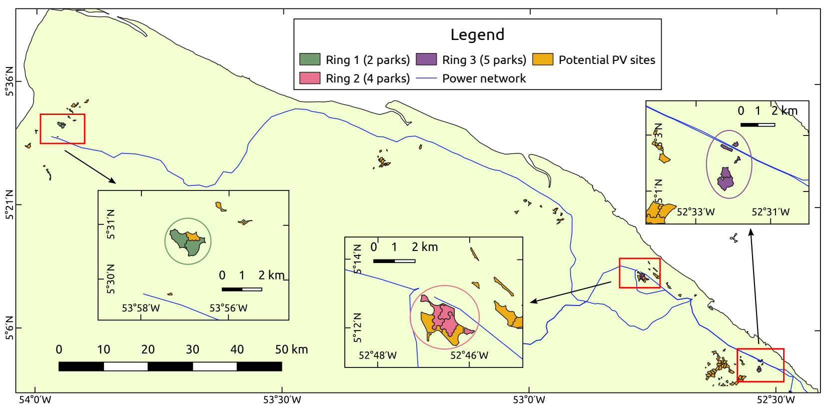
(a) site capacity $\leqslant$ 5 MW, no limitation on ring hosting capacity

(b) Site capacity $\leqslant$ 20 MW, Ring hosting capacity $\leqslant$ 20 MW

Figure 4. Pareto solutions for ring and site approach.



(a) Selected PV sites in *site approach* (site capacity $\leqslant$ 20 MW)



(b) Selected rings in *ring approach* (ring hosting capacity $\leqslant$ 20 MW)

Figure 5. site vs. ring approach spatial results for Pareto solution of Figure 4b (selected cost value = 80 M€).

When only small-scale solar PV sites can be integrated into a power network (a), the Pareto solutions depicted in Figure 4a show that the ring approach gives better results, with for instance 10 MW of extra installed power and 16 GWh of extra power generation compared to the site approach for the same overall cost (60 M€). When both approaches are subject to the same constraints (b), the resulting Pareto solutions remain similar in both cases regardless of the cost value (see Figure 4b). However, as stated in section 2.1, small-scale power stations allow for more manageable risk adversity once it is operating. Hence the ring approach gives the best energy planning strategy with respect to both the decision maker and the network manager needs.

To describe the resulting spatial difference between both models, we plot in Figure 5 the selected PV sites against the selected rings regarding the second case (Figure 4b) and with respect to the same Pareto solution (cost value = 80 M€). In both examples, the selected PV sites are scattered throughout the Northern shore of French Guiana, along the power network (i.e. cost is lower for sites close to the grid). The total installed power is similar (45.4 MW against 44.9 MW) but is allocated among 3 facilities in the site approach (Figure 5a), and among 3 rings and 11 small-scale facilities in the ring approach (Figure 5b). The characteristics of the PV sites in both examples are given in Table 2 and Table 3.

Table 2. Characteristics of the solar PV sites depicted in Figure 5a

site ID	Nominal power (MW)
site 1	6.87
site 2	20
site 3	18.52
Total	45.39

Table 3. Characteristics of the rings depicted in Figure 5b

Ring ID	Number of sites	Installed power (MW)	site capacities (MW)
Ring 1	2	5.56	{4.72, 0.84}
Ring 2	4	19.3	{5, 5, 4.74, 4.56}
Ring 3	5	19.99	{5, 5, 5, 2.8, 2.19}
Total	11	44.85	—

4 Conclusion

In this paper, we exploited the strengths of spatial decision support, applied to the field of energy transition. In particular, we studied the integration of spatial analysis on spatio-temporal data (solar radiation) as a pre-processing step to an optimization module. This module introduces a novel approach to planning the placement of solar PV sites, given the GIS computation of potential sites, such that the costs are further optimized compared to a more traditional approach. We showed and modelled an analogy with the SONET model, to aggregate potential sites around one shared substation that feeds the power grid. The results show substantial gain in costs per KWh produced, as well as enhanced energy stability and risk management given a larger number of selected sites. Further and ongoing work include the extension of our GIS and optimization model, to assess biomass potentials and its energy power embedded into the grid.

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