IMPACT OF THE LOAD MODELING ON THE OPTIMAL SELECTION OF ROOFTOP SURFACES FOR PV INSTALLATION

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Abstract: Simultaneous consideration of various aspects of urban area, such as time-dependent distribution network (DN) operation and solar energy availability, allows the development of the advanced algorithms for integration of photovoltaic (PV) systems. This paper represents further developments in the previously proposed methodology for determining rooftop surfaces suitable for the installation of PV systems. Differential evolution-based optimization methodology simultaneously considered a high-resolution spatio-temporal PV potential data and a time-dependent operation of DN of a known configuration. This paper identifies another aspect, important for solving the problem of PV system accommodation. It evaluates how dependency of power consumed from a supply voltage affects the levels of PV systems a network is capable of accommodating, as well as the optimal selection of rooftop surfaces for PV installation. Case study on a real urban low voltage DN shows how two extreme cases of load representation (i.e., constant power and constant impedance loading models) affect the optimal selection of rooftop surfaces for PV Installation.

Keywords: distribution network, loading models, PV accommodation, loss minimization

1 Introduction

Integration of the distributed generation units into the electricity distribution networks (DNs) is proliferated by the technological development as well as the current political and environmental directives and incentives. Slovenia is considered to be a country with an underutilized solar potential [1]. Therefore, the rooftop surfaces of its urban areas offer a possible solution to a larger scale integration of the photovoltaic (PV) systems into the low voltage parts of its DNs. However, in order to identify the rooftop surfaces, which are the most suitable for the PV installation, a wholesome approach should be considered and both time-dependent network operation as well as the behavior of the loads should be considered, simultaneously with the actual data regarding the availability of the solar energy on a considered area.

A previous research work of the authors includes the development of a methodology for determining rooftop surfaces suitable for the installation of PV systems, based on a simultaneous consideration of a PV potential assessment and time-dependent DN operation [2]. LiDAR (Light Detection And Ranging) data and long-term direct and diffuse irradiance measurements by a pyranometer were used for performing a high resolution, spatio-temporal assessment of the solar and PV potential [3], [4]. However, the rooftop surfaces rated as highly suitable for PV installation from the solar energy availability are not necessarily the most suitable from the network operation standpoint. Generation units, which are poorly sited and sized may cause reverse power flows, increase power losses or violation of voltage constraints [5]. Therefore, a model of a DN supplying the network, together with the measured time-dependent profiles of the power loading, were utilized to assess the impact that the additional PV generation might have on a network operation. Additionally, it has been shown that a greater reduction of power losses and increased capability for PV accommodation can be achieved by allowing hourly change in network configuration [6] and active participation of an on-load tap changer equipped distribution substation [7].

The initial methodology considered that the power consumed by the loads is independent from the supply voltage, i.e. all loads were presented using a constant power loading model. However, if the loads in the network behave differently and their consumption changes with the supply voltage, the impact of the additional PV generation on power losses changes as well. This paper, therefore, evaluates the impact that the different loading models have on optimal selection of rooftop surfaces for PV installation. A polynomial model of the active and reactive power consumed in a node is utilized [8] in order to adequately describe the dependence of the power consumed on the supply voltage. A problem of load modelling, such as selection of static or dynamic load model structure or deriving load model parameters has already been addressed in the literature, and the additional information on the subject can be found in [9]–[11]. This paper will, however, only consider two extreme cases of load representation, i.e., all loads in the network will be represented using a constant power or constant impedance loading models. An identification of the exact parameters of the loads in a specific network, although important, exceeds the scope of this paper.

The paper is structured as follows. The second section describes the methodology for determining suitability of rooftop surfaces for PV installation and the loading models used for representation of the dependency of power consumed on supply voltage. The third section describes a test site, selected for evaluating the impact of the load modeling on the optimal selection of rooftop surfaces for PV installation. The results of a case study are presented in the fourth section, followed by the fifth section, which gives the final remarks and concludes the paper.

2 Methodology

A comprehensive description of the procedure for determining rooftop surfaces suitable for the installation of PV systems, utilized in this paper, can be found in [2]. However, a brief description of the procedure is given hereinafter for the sake of clarity.

2.1 Procedure for determining suitability of rooftop surfaces for PV installation

The procedure is based on a simultaneous consideration of different aspects of urban area, presented as layers in Figure 1. These layers overlap in order to create a wholesome approach to solving the problem of optimal selection of rooftop surfaces for PV installation. At the beginning, a preprocessing of the remote sensing data (**layer 1**) for a selected urban area (**layer 0**) is used for assessment of solar and PV potential (**layer 2**). The assessment procedure considers a direct and diffuse solar irradiance as well as nonlinear efficiency characteristics and ageing of monocrystalline PV modules with solar inverters, their inclination and shadowing from surrounding terrain and vegetation. This allows the creation of average hourly profiles of electrical energy generation for every day in a year, with the 0.5 m^2 resolution. Mathematical representation of a DN supplying the considered urban area is built (**layer 3**) and equipped with the time-dependent loading and generation profiles, based on the long-term measurements in multiple points of a discussed network (**layer 4**). Evaluation of the network operation and calculation of the nodal voltages, line currents and network losses are performed through a series of time-discrete load flow calculations. A method chosen for these purposes is a "*backward-forward sweep*" method [12]. The optimization procedure that allows the selection of optimal rooftop surfaces (**layer 5**) is achieved by simultaneous consideration of the underlying layers.

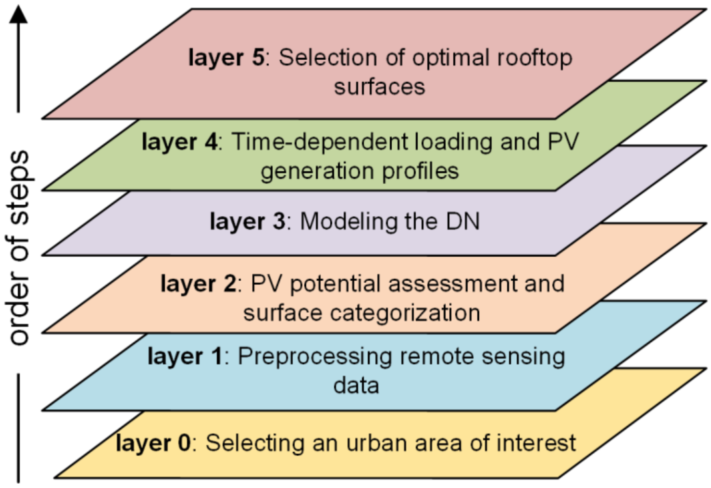

Figure 1: Representation of a methodology for selection of rooftop surfaces, using overlapping layers.

A simplified block diagram of the methodology is presented in Figure 2. The figure illustrates how the methodology is a two-step procedure that combines results of an optimization module (**layer 2** and **layer 3** in Figure 1) and solar and PV assessment module (**layer 1** and **layer 2** in Figure 1) in order to performed a selection procedure (**layer 5** in Figure 1).

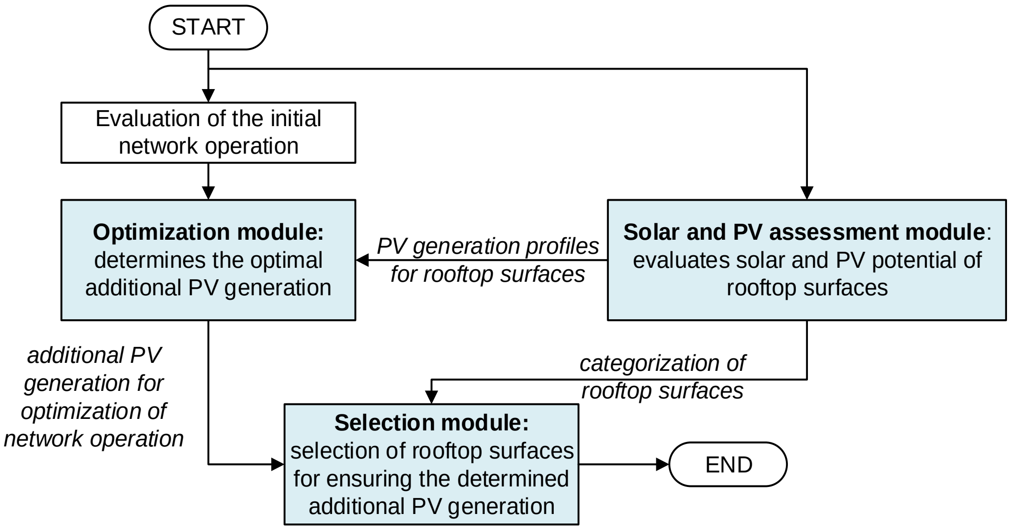

Figure 2: Simplified block diagram of the procedure for determining rooftop surfaces, suitable for PV system installation.

Firstly, an operation of the original network without the additional generation units is evaluated, through series of time-discrete load flow calculations. Then, the optimization module (see Figure 2), utilizes a metaheuristics called Differential Evolution (DE) [13] to find such additional PV generation that yields minimum annual energy losses in the network. The optimization algorithm also ensures the proper voltage profiles and prevents the thermal overloading of the power lines. The objective function minimized in the optimization module, q_{fun} (1), is defined as the quotient of the annual electric energy losses of the currently evaluated solution $W_{\mathrm{loss}_{\mathrm{addPV}}}$, and the losses of the original network $W_{\mathrm{loss}_{\mathrm{orig}}}$.

$$q_{\mathrm{fun}} = \frac{W_{\mathrm{loss}_{\mathrm{addPV}}}(\boldsymbol{x}_{\mathrm{p}})}{W_{\mathrm{loss}_{\mathrm{orig}}}} + p \tag{1}$$

The value of the objective function q_{fun} depends on a currently evaluated vector of search parameters $\boldsymbol{x}_{\mathrm{p}} = \{x_{\mathrm{p},1}, x_{\mathrm{p},2} \dots x_{\mathrm{p,n}}\}$ and penalties p, which ensure that the voltage profiles are kept within the prescribed limits and thermal overloading of lines is prevented. An element of a vector of search parameters $x_{\mathrm{p,i}} \in \boldsymbol{x}_{\mathrm{p}}$, determined by the DE, represents a relative share of all the available PV generation which could be achieved from the rooftop surfaces, corresponding to the i^{th} LV consumer. Each element of a vector is found on an interval as given in (2).

$$x_{\mathrm{p,i}} \in [0,1] \tag{2}$$

The value 1 means that the optimal PV generation for minimization of the annual energy losses is achieved when all the rooftop surfaces, associated with the location of the i^{th} LV consumer, are utilized for installation of PV systems. On the other hand, the zero value indicates that no additional generation is required, and none of the rooftop surfaces should be selected. When the value is between the two extreme values, only the information regarding a relative share of the available PV generation is determined. The exact rooftop surfaces that will ensure the additional power generation, required for the minimization of energy losses are determined based on their categorization regarding suitability for PV installation from the PV potential point of view. The selection is performed in such a way that surfaces of higher ratings have priority in the selection process, i.e. are selected first, and followed by those of lower ratings. A part of the rooftop surfaces can be utilized in cases where the consideration of the whole surface would exceed the required generation [2].

2.2 Loading models

Loads and generation units are in a DN defined by a complex power they consume $\underline{S}_{\mathrm{load}}$ or generate $\underline{S}_{\mathrm{gen}}$. However, the value of an active and reactive power consumed at a node n ($P_{\mathrm{load,n}}$ and $Q_{\mathrm{load,n}}$ respectively) may be dependent from the system voltage $\underline{U}_{\mathrm{n}}$, a load is supplied by. To describe this dependency, polynomial models of an active (3) and a reactive power (4) are used in this study [8].

$$P_{\mathrm{load,n}} = P_{\mathrm{load,n}} \left(a_0 + a_1 |\underline{U}_{\mathrm{n}}| + a_2 |\underline{U}_{\mathrm{n}}|^2\right) \tag{3}$$

$$Q_{\mathrm{load,n}} = Q_{\mathrm{load,n}} \left(r_0 + r_1 |\underline{U}_{\mathrm{n}}| + r_2 |\underline{U}_{\mathrm{n}}|^2\right) \tag{4}$$

Coefficients that describe a constant power, constant current and constant impedance behavior of the loads are the pairs of coefficients(a_0, r_0), (a_1, r_1) and (a_2, r_2), respectively. They represent the independence, linear dependency and quadratic dependency of the power consumed from the voltage at the supply node. Each coefficient gives the share of single model in the whole polynomial model, and the coefficients sum up to the value one (5a) and (5b).

$$a_0 + a_1 + a_2 = 1 \tag{5a}$$

$$r_0 + r_1 + r_2 = 1 \tag{5b}$$

Another example of mathematical description of the relationship between the active and reactive power consumed and the supply voltage would be the aggregated load model, as presented in [14].

3 Case study

The evaluation of the impact of the load modeling on the optimal selection of rooftop surfaces for PV installation has been performed through a case study. A real urban low voltage distribution network, a part of the electricity system supplying the city of Maribor, was selected as a test site. Figure 3 presents the single line diagram of a considered network, composed of 38 nodes and 37 line segments, supplying 24 LV consumers. However, the data regarding the solar irradiance on the adjacent rooftops was unavailable for two consumers. The remaining 22 consumers were considered for the possibility of the additional PV installation and the number of search parameters in the optimization procedures is 22 (6).

$$\boldsymbol{x}_{\mathrm{p}} = \{x_{\mathrm{p},1}, x_{\mathrm{p},2} \dots x_{\mathrm{p},22}\} \tag{6}$$

Polygons of different colors in Figure 3 represent rooftop surfaces with the PV assessment performed, considered for possible PV installation. The considered 69 polygons are colored, based on their suitability for PV installation from the PV potential standpoint as presented in Figure 3. Categorization of the polygons by the connection to the LV consumer, into 22 categories, is presented in Figure 4.

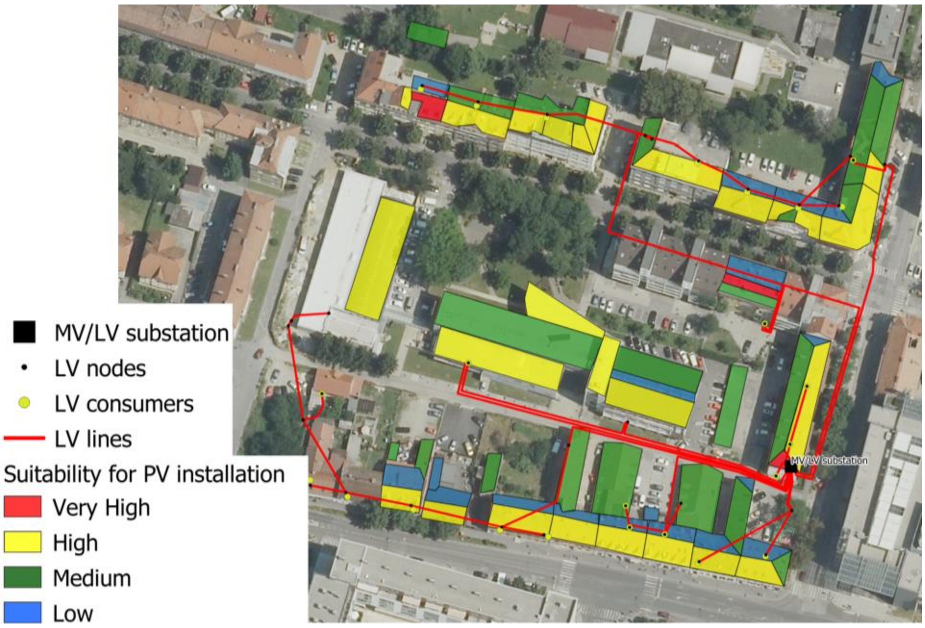

Figure 3: Low voltage test site.

Figure 4: Categorization of rooftop surfaces by the corresponding LV consumers.

This paper will consider only two extreme cases of behavior of all the loads in the network:

- *constant power loading model* (**CPM**), where the polynomial coefficients have the following values: $a_0 = r_0 = 1$ and $a_1 = a_2 = r_1 = r_2 = 0$.
- *constant impedance loading model* (**CIM**), where the polynomial coefficients have the following values: $a_2 = r_2 = 1$ and $a_0 = a_1 = r_0 = r_1 = 0$.

4 Results

The following section presents the results of the evaluation of the impact of load modelling on selection of rooftop surfaces. Furthermore, the reduction of annual energy losses achieved and assessment of total rated power of the PV systems that could be installed are for **CPM** (constant power loading model) and **CIM** (constant impedance loading model) determined as well.

4.1 Evaluation of the original network operation

Firstly, the initial network operation, without the additional PV systems, will be evaluated. Transformer substation supplying the considered network is assumed to have a tap changer position set to the value $+2 \times 3.33\%$, i.e. voltage of a slack bus is $U_{\mathrm{slack}} = 1.0666\ \mathrm{p.u.}$ Load flow calculations are for the original network performed for every hour of an average day in a month. The annual energy losses are determined for consumers in the network being represented using two extreme cases: **CPM** and **CIM**. Determined annual losses of the original network are 57.78 MWh and 63.65 MWh for CPM and CIM respectively.

Distribution of nodal voltages, determined for every node in a considered DN and for every hour of an average day in a month are presented in Figure 6, for two loading models (**CPM** and **CIM**). Two histograms in Figure 6 show that when CIM is considered, the nodal voltages in the system are somewhat reduced thorough the year. The power loading for **CIM** changes with the square of the nodal voltage. Voltages, higher than the base value (1 p.u.) will therefore cause the power loading to increase. Increased loading yields a greater voltage drop along the lines and greater annual energy losses, as already determined. However, the additional generation units in the network will cause the increase of voltage profiles. Therefore, it is expected that in the case of **CIM** a greater total installed power of PV systems could be accommodated, as there is more reserve before the upper voltage constraint (1.1 p.u.) is violated.

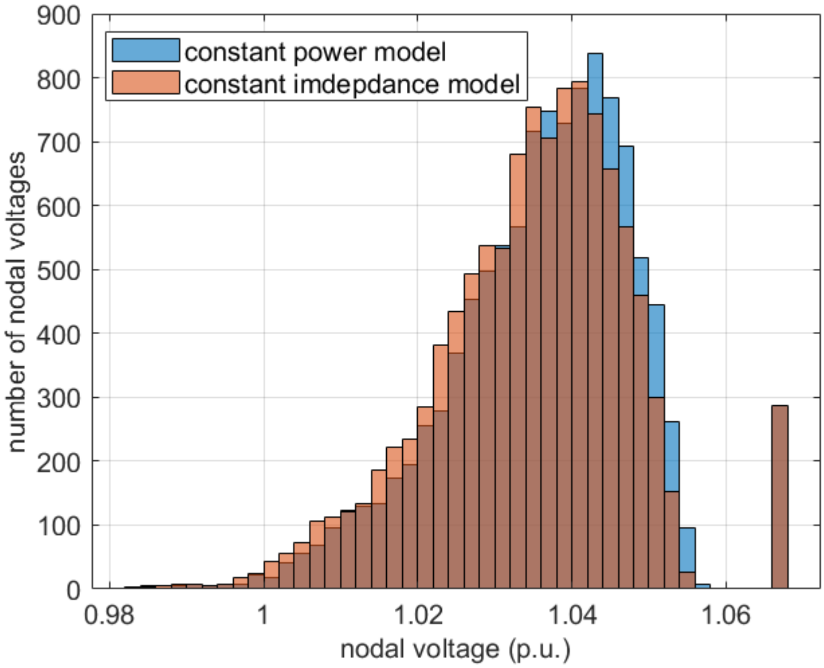

*Figure 5: Distribution of nodal voltages in the original network (**CPM** and **CIM**).*

4.2 Impact of the load modeling on the PV accommodation

The optimization part of the proposed procedure determined that the relative reduction of annual energy losses in both cases is approximately the same and equals 32.9% for **CPM** and 31.2% for **CIM**. However, the main difference, as previously assumed, is observed in the total installed power of PV systems the network would be capable of accommodating. When the loads in the network are represented using **CIM**, 20.9°kWp more PV systems could be accommodated than in a case of **CPM** (relative increase of 7.8%), as presented in Table 4.1.

Table 4.1: Summary of the results.

	constant power loading model	**constant impedance loading model**
Original network losses	57.78 MWh	63.65 MWh
Losses after the optimization	38.79 MWh **(32.9% reduction)**	43.19 MWh **(32.1% reduction)**
Rated power of installed PV systems	267.0 kWp	287.9 kWp
Number of selected rooftop surfaces	32 whole, 11 partial	34 whole, 9 partial

These results are obtained with the relative shares of the additional PV generation per LV consumer, as presented in Figure 6. It is observed that the **CIM** allows up to 20% greater accommodation of PV systems that **CPM** example of the LV node, represented by the search parameter x_{p2}.

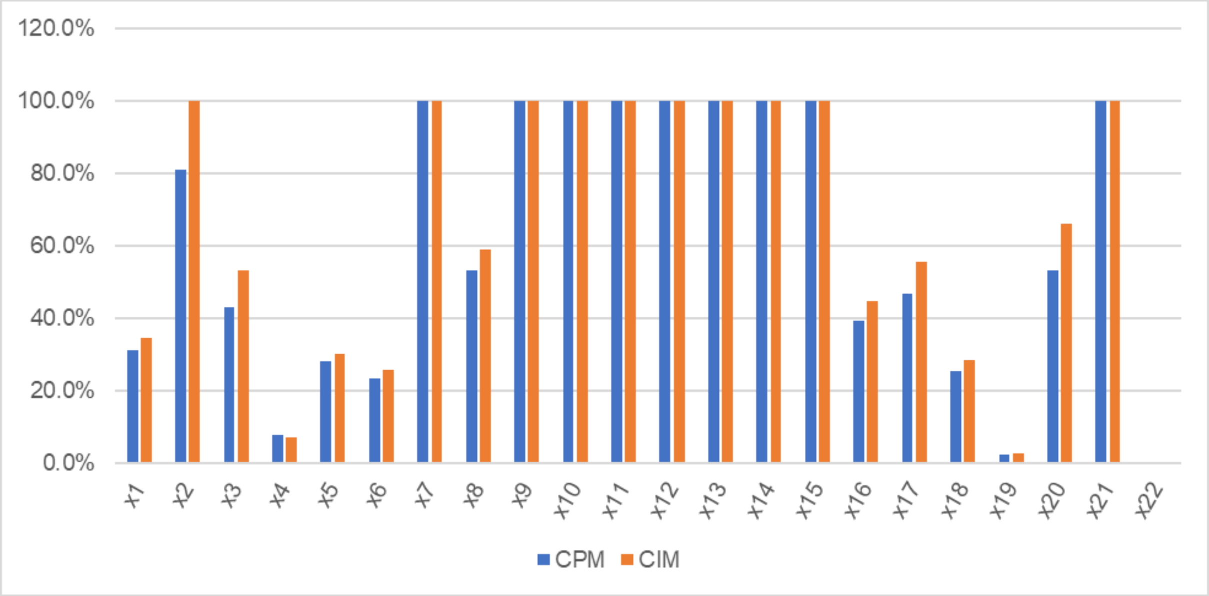

*Figure 6: Relative shares of the additional PV generation per LV consumer (**CPM** and **CIM**).*

The optimization part of the procedure determined only the relative shares of total rooftop surfaces per LV consumer. Then, the selection part of the procedure determined the exact rooftop surfaces that could generate such additional power, determined as optimal in the optimization part of the procedure.

The selected rooftop surfaces are presented in Figure 7 for **CPM** and **CIM**. When **CPM** is considered, 32 whole and 11 partial rooftop surfaces that yield 267.0°kWp of total installed power are selected. In other case (**CIM**), 34 whole, 9 partial rooftop surfaces that yield 20.9°kWp more, are selected. Even though the number of total rooftop surfaces does not change, the percentages of the partial rooftop surfaces are greater for **CIM**. In both cases 26 rooftop surfaces were considered as unsuitable for PV installation, since rooftop surfaces of the higher suitability for PV installation from the PV potential standpoint ensured the required power generation and had priority in the selection procedure.

The results show, as in our previous research, that even though the surfaces are categorized as being highly suitable for PV installation from the PV potential standpoint, they are not necessarily optimal from the network operation standpoint as well.

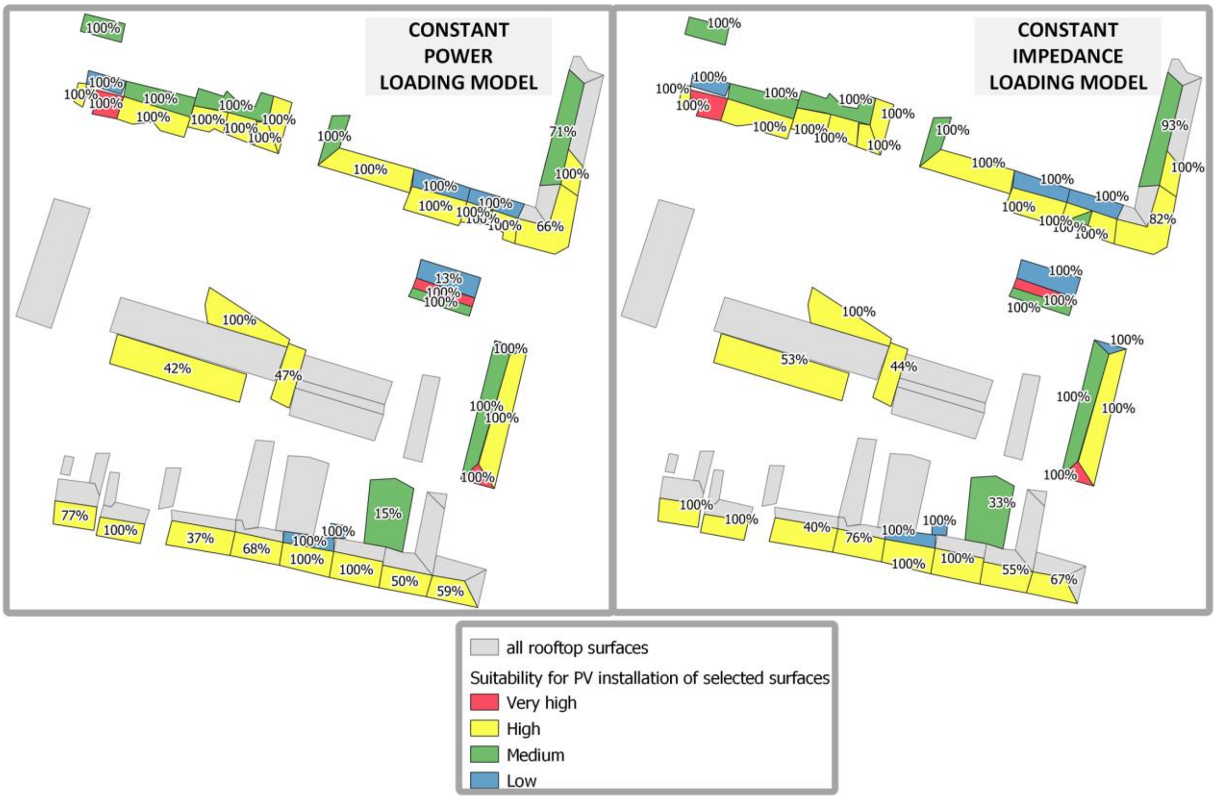

*Figure 7: The results of rooftop surface selection procedure (**CPM** and **CIM**).*

5 Conclusion

The aim of this paper was to evaluate how behavior of the loads in the network impacts the process of the selection of rooftop surfaces, suitable for the installation of PV systems. The paper firstly described a methodology used for determining rooftop surfaces suitable for installation of PV systems, from both PV potential and distribution network operation standpoints. However, some of the loads in a network change their active and reactive power consumed with respect to the supply voltage. Therefore, the necessity to assess the difference in the network operation and PV system accommodation, with respect to different loading models, was identified.

The paper considered two extreme cases of loading models. Namely either all loads in the considered network were assumed to be independent from the supply voltage (constant power loading model), or they showed a quadratic dependency on it (constant impedance loading model). The results of the case study, performed on a real urban low voltage network showed, that CIM results in increase of the power consumed. Greater loading in the network means reduction of voltage profiles, thus allowing a 7.8% greater total installed power of PV systems, as there was more reserve before the upper voltage constraint could be violated.

The observations and findings presented within this paper are currently being used in a development of a wholesome approach to optimization of distribution network operation by optimal integration of renewable energy resources and active participation of different elements in a modern network. This paper showed that the constant power loading model is insufficient in detailed consideration of network operation. This is especially important when considering active network elements that will bring greater variability in voltage profiles across the DNs, thus strongly influencing the optimal accommodation levels for PV systems.

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