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## Highlights

### **Optimization of the integration of photovoltaic systems on buildings for self-consumption - Case study in France**

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- Different objectives related to PV self-consumption are defined
- The optimization of PV integration according to these objectives is analyzed
- Roof and façades are considered
- A parametric study is carried out to study the influence of the sizes of the building and its energy consumption on the optimal PV integration

# Optimization of the integration of photovoltaic systems on buildings for self-consumption - Case study in France

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## Abstract

The massive deployment of Photovoltaic (PV) energy in cities, which is expected in the coming years, brings new challenges when it comes to controlling power variations inherent to the impact of high PV penetration on the economy, energy exchanges and grid stability. In this perspective, self-consumption, which consists in consuming locally a part of the produced PV energy, allows to smooth the variations in the solar power production, and therefore reduce the stress on the grid. Among other strategies, self-consumption can be enhanced by the adequate use of all the surfaces of a building (roof and façades). In the present work, the optimization of the PV integration on the roof and façades of a building, is performed in order to optimize objectives related to self-consumption. These objectives are based on different aspects of self-consumption: minimizing the exchanges of energy with the grid, improving grid stability, or maximizing the economic profitability. The case of France will be considered. The influence of different parameters, namely, the load profile, the building consumption and height, on the optimal integration of PV will be investigated. It is shown that the optimal PV integration is drastically impacted by the studied parameters, and the goal of the optimization. Furthermore, integration on façades appears to be most of the time relevant in order to enhance self-consumption.

*Keywords:* photovoltaic integration, solar building, self-consumption, optimization, façade integration

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## 1. Introduction

2 Repeated and constant calls to action leave no doubt as to the need for rapid and far-reaching  
3 responses to initiate and carry out a massive energy transition [1, 2].

4 Cities are directly responsible for about two-thirds of the world's final energy use, as well  
5 as 75% of global carbon dioxide (CO<sub>2</sub>) emissions. In addition, cities concentrate 55% of the  
6 world's population and 80% of the world's gross domestic product. Thus, the shift to renewable  
7 energy in cities is essential to decarbonize the global energy system [3]. Among the renewable  
8 energies, Photovoltaic (PV) solar energy is particularly suited for urban environment. Indeed,  
9 cities represent areas with high energy consumption. In these areas, a lot of unused surfaces  
10 (roofs and façades) could be used for the harvesting of solar energy.

11 Power generation using PV technologies has experienced sustained and accelerated expansion  
12 since its commercial development a few decades ago. In 2019, accounted for 2.6% of the  
13 global electricity production and is expected to cover 25% of the world's electricity needs by  
14 2050 [4]. It is also estimated that 40% of this energy will be produced from building integrated  
15 PV panels [4].

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16 However, a high penetration rate of PV energy raises issues especially those of the intermit-  
17 tent and variable features of the solar resource and the management problems of the grid they  
18 may cause [5, 6, 7, 8]. One of these challenges concerns the excess of production of PV energy,  
19 which can cause reverse power flows. These can destabilize the stability of the electrical grid  
20 [5, 9, 7]. Sudden variations in the electrical power load, also called ramp rates, also represent an  
21 issue when high levels of PV penetration are reached [10].

22 To address these challenges, different strategies have been developed in order to limit and/or  
23 smoothen these variations. Among them, the use of storage and curtailment [11, 12], higher  
24 flexibility, or load shifting to limit overproduction [9], have proven relevant. Another way to  
25 reduce the impact on the grid is to inject less energy in it by consuming a part of the PV energy  
26 production locally [13, 11]. This is referred to as self-consumption, which is particularly adapted  
27 to urban environments where each building is a consumer as well as a potential producer of  
28 energy.

29 The two most common configurations for self-consumption are the on-grid and the off-grid  
30 configurations. The off-grid configuration consists in a building equipped with PV systems which  
31 is not connected to the grid. In this case, all the produced energy from the PV systems must be  
32 consumed by the building, either through direct use or by using storage. In Europe, the off-grid  
33 configuration corresponds to a small minority of the cases and has, by definition no impact on the  
34 electrical grid. The on-grid configuration is a building equipped with PV systems, which injects  
35 whole or a part of its PV production to the grid. This configuration represents the large majority  
36 of the cases, especially in urban environments.

37 Limiting reverse power flows and ramp rates are objectives at the scale of a region/territory.  
38 For that reason, the use of self-consumption to smoothen load variations on the grid is relevant  
39 for grid managers or policymakers whose goal is to accelerate energy transition on their territory.  
40 However, building owners are probably less aware of these challenges and will consider self-  
41 consumption as a way to increase the economic profitability of a PV system [13, 14, 15]. For that  
42 reason, enhancing self-consumption can have different interpretations depending on the objective  
43 that is pursued.

44 The vast majority of studies on the impact of urban PV on the grid only considered rooftop  
45 PV systems, mostly because of their maturity, their easy integration and their low cost. However,  
46 the strong decrease in prices of PV systems, which is likely to continue in the coming years  
47 [16, 17], allows to consider the integration of PV on vertical façades as economically viable.  
48 This opens engaging perspectives in urban environments where the available area on façades is  
49 sometimes much larger than that on roofs [18, 19].

50 One of the specificity of PV on façades is to have different profiles of power production  
51 different from those of PV on the roof. Indeed, east and west oriented PV panels have their peak  
52 production shifted compared to a roof-integrated PV. This allows them to produce more energy  
53 in the morning and evening [20, 19]. Panels installed on the southern façades are relatively less  
54 affected by seasonal variations [21]. Therefore, the optimization of PV integration, including all  
55 façades, appears as an interesting strategy to enhance self-consumption.

56 Optimization of the harvesting of solar energy has mainly been conducted by optimizing  
57 urban design in order to maximize the collection of solar energy (see e.g. Kämpf et al. [22],  
58 Bizjak et al. [23]). In recent years, particular focus has been on optimizing the matching between  
59 energy consumption and solar production (see e.g. Widén et al. [24], Natanian et al. [25], Waibel  
60 et al. [26]). These studies optimized the whole urban design *i.e.* the shapes and orientations  
61 of buildings. However, building new district is costly and time-consuming. It is therefore very  
62 likely that most of the PV systems will be installed on existing buildings.

63 Some studies have recently focused on the optimal integration of PV on the roofs and façades  
64 of existing buildings. Brito et al. [27] showed that under Mediterranean latitude, the power pro-  
65 duction of the façades was better matching the building load, therefore reducing the net energy  
66 load on the grid. Freitas et al. [28] conducted a study on the optimization of PV production  
67 on roofs and façades on the scale of districts and showed the importance of PV integration on  
68 façades, especially for the reduction of the ramp-rates and increase in self-consumption. How-  
69 ever, Freitas et al. [28] showed that, for a same installed capacity, the PV integration varied  
70 drastically if surfaces that are the most irradiated are used first, or if the surfaces are selected in  
71 order to maximize the self-consumption rate.

72 All these studies focused on the district scale and conducted the optimization by considering  
73 the entire façade of a building. However, because of technical, energetic or economic constraints,  
74 it often occurs that only a certain part of the roof area is suitable for PV integration [29, 30]. As  
75 a consequence, integrating PV system on the entire façade of a building, when it is possible, is  
76 likely not to be considered optimal, depending of the pursued objective.

77 The aim of the present work is to investigate the optimal integration of PV on building sur-  
78 faces considering different self-consumption objectives. The first objective is the maximization  
79 of the load match. In this case, the PV systems are integrated so that the power production of  
80 the PV matches as closely as possible the building load. This results in a reduction of the energy  
81 interactions between the grid and the building equipped with PV. The improvement of the load  
82 match has been used in several studies (see e.g. [24, 25]). The second objective aims to re-  
83 duce the occurrence and intensity of the ramp-rates in the power exchanges between the building  
84 equipped with PV and the grid. The third objective is economic and consists in maximizing the  
85 profitability of the system.

86 The main contributions of the present work are:

- 87 • Defining different metrics related to self-consumption and presenting the associated opti-  
88 mal integration of PV systems,
- 89 • Investigating the influence of the size of the building and its consumption on the optimal  
90 integration of PV systems,
- 91 • Studying the role of the façade integration of PV panels in order to enhance self-consumption.

92 Optimal PV configuration is highly dependent on the local context. Indeed, differences in  
93 latitude and longitude have a significant impact on the integration on the façade. Furthermore,  
94 the local economic context also has a strong influence on the optimization of the PV integration.  
95 For that reason the present work will be illustrated in the French context.

## 96 2. Methodology

### 97 2.1. Geometry and usable surfaces

98 A single building with a flat roof will be considered here. This building will have a footprint  
99 area equal to the roof surface area of  $S_r = 10 \times 10 m^2$ . For the sake of clarity we also neglect  
100 the wall width so that  $S_r$  is also equal to the area of a floor  $S_f$ . The building is composed of  $N_f$   
101 floors, each floor being 3 m high. Three of these buildings are illustrated in Figure 1. They have  
102 respectively  $N_f=2, 5$  and 10 floors and will be further referred as ‘low-rise’ ‘mid-rise’ and ‘high-  
103 rise’ buildings. The surfaces are aligned with the cardinal directions. Note that, unlike what is

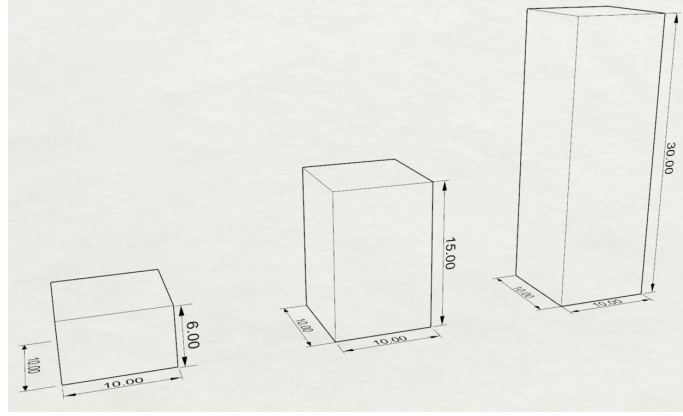


Figure 1: Geometry of the 'low-rise', 'mid-rise' and 'high-rise' buildings

104 seen in Figure 1, these buildings are considered to stand alone, without any possible shading from  
 105 other buildings.

106 The roof as well as the east, west and south façades will be considered in the present work.  
 107 The north façade is disregarded as it is shaded most of the time. On the roof, the PV systems are  
 108 tilted at an angle of  $30^\circ$ , facing the south, and cannot occupy more than 70% of the surface to  
 109 avoid self-shading [31]. For a building of  $N_f$  floors, the total living area corresponds to  $N_f \times S_f$ .  
 110 According to the French building standards, the glazed surface on the façade must cover at least  
 111  $1/6$  of the total living area. Now, considering that the glazed surfaces are equally shared between  
 112 the four vertical façades, on each façade the usable surface is reduced by a quarter of the total  
 113 glazed area. Therefore, the usable surface area of each façade is equal to

$$S_{u,i} = S_{T,i} - \frac{1}{4} \times \frac{N_f \times S_f}{6}, \quad (1)$$

114 Where  $S(m^2)$  refers to a surface area, the subscripts  $T$  and  $u$  respectively refers to the total and  
 115 the usable surface area of a façade. The subscript  $i = e, w, s$  refers to the east, west and south  
 116 façades.

## 117 2.2. Production and consumption of the building

118 In what follows,  $P$  (kW) and  $L$  (kW) will correspond respectively to the power production  
 119 and the power consumption (load) of the building. It is also considered here that the energy  
 120 produced by the PV system is used for the building energy needs. Only when the PV production  
 121 exceeds the building energy needs, the excess of production is sold to the grid. Therefore the  
 122 self-consumed energy during a period  $T$  is defined by

$$E_{sc} = \int_T \min(P(t), L(t)) dt. \quad (2)$$

123 The energy sold to the grid, which corresponds to an excess of production that cannot be con-  
 124 sumed locally, is defined by

$$E_e = \int_T \max(P(t) - L(t), 0) dt. \quad (3)$$

125 In order to quantify power and energy exchanges between the building equipped with PV  
 126 systems and the grid, the residual load  $L_r(t)$  (sometimes called residual or net load) is introduced.  
 127 It is defined as the difference between load and production *i.e.*.

$$L_r(t) = L(t) - P(t). \quad (4)$$

128 In the present problem, it is considered that there are no shades from the surroundings so that  
 129 the received solar irradiation is uniform on each surface. Thus if we consider  $p_k(t)$  ( $kW/m^2$ ) the  
 130 PV production per surface area with  $k \in \{r, e, w, s\}$ , the building's PV power production can be  
 131 expressed as

$$P(t) = \sum_{i=r,e,w,s} S_{PV,i} \times p_i(t) \quad (5)$$

132 where the  $PV$  index indicates the surface covered by the PV panels. For  $i \in \{r, e, w, s\}$ , we have  
 133  $0 \leq S_{PV,i} \leq S_{u,i}$ . Note that in equation 5, we neglect non-linear phenomena that may impact the  
 134 total PV production. Indeed, several factors may impact the PV production, the temperature of  
 135 the PV systems being one of the best known and most influential [32], [33]. However, here, the  
 136 fact that the building is considered to stand-alone, without any surrounding buildings, drastically  
 137 reduce the urban heat island effect. Moreover, the loss of performance would correspond to  
 138 some % during the hottest day [32], which would not significantly change the results of the  
 139 present work. As a matter of fact, most of the studies that were mentioned in the introduction  
 140 neglect the influence of temperature on the PV production.

### 141 2.3. Self-consumption and optimization objectives

142 One of the main goals of the global PV deployment is to drastically increase the share of  
 143 PV production in the energy mix. To achieve this objective at the scale of building, all possible  
 144 available areas (roof and façades) should obviously be covered by PV panels. However, this  
 145 objective is different from the objective related to self-consumption, in which a certain balance  
 146 between production and consumption should be considered.

147 First of all, we define the classical metrics of self-consumption [13] which are the rate of self-  
 148 consumption,  $\tau_{sc}$ , and the rate of self-sufficiency  $\tau_{ss}$ . The self-consumption rate  $\tau_{sc}$  is defined  
 149 as the share of the total PV production that is consumed by the building. The self-sufficiency  
 150 rate  $\tau_{ss}$  is defined as the share of total building energy demand that is being supplied by the PV  
 151 systems *i.e.*:

$$\tau_{sc} = \int_T \frac{\min(P(t), L(t))}{P(t)}, \quad \tau_{ss} = \int_T \frac{\min(P(t), L(t))}{L(t)}, \quad (6)$$

152  $T$  being the considered time period, in this case a year.

153 These two metrics cannot be considered here as objectives in mono-objective optimization.  
 154 Indeed, a self-consumption rate of 1 is always achievable if the PV energy production is low  
 155 enough in comparison with the energy needs of the building. Conversely, in order to maximize  
 156 self-sufficiency, it is sufficient to maximize PV production. However, as mentioned in the intro-  
 157 duction, self-consumption allow to attenuate some of the interactions with the grid, and neither  
 158 the maximization of  $\tau_{sc}$  nor this of  $\tau_{ss}$  can guarantee this.

159 The optimization of PV integration will therefore be done according to other objectives. The  
 160 first one corresponds to a minimization of energy exchanges with the grid. The second one  
 161 is based on the minimization of the reduced load variations, and the third one is an economic  
 162 objective, based on a maximization of the  $NPV$  (Net Present Value).

163 *2.3.1. Objective 1: Minimization of the energy exchange with the grid*

164 The first optimization objective consists in minimizing energy exchanges between the build-  
 165 ing and the grid. This corresponds to minimizing

$$E_{grid} = \int_T |L_r(t)| dt. \quad (7)$$

166 This objective allows to obtain the best matching between the PV production and load of the  
 167 building. This is particularly interesting in order to limit the oversupply or undersupply of solar  
 168 energy on the grid which would be induced by a massive increase in decentralized PV systems,  
 169 as mentioned in the introduction.

170 In order to assess the efficiency of the integration, an Energy Exchange (EE) indicator will  
 171 be defined as

$$\tau_{EE} = \frac{E_{grid}}{\int_T |L(t)| dt}. \quad (8)$$

172 This indicator is defined as the amount of energy exchanged with the grid by a building equipped  
 173 with PV panels, divided by the amount of energy exchanged by the same building but without  
 174 any PV panels. In other words, this indicator quantifies to which extent the PV panels reduces  
 175 or increases the stress on the grid compared to the same building without PV. When  $\tau_{EE} < 1$ ,  
 176 the PV integration reduces the energy interactions with the grid, whereas when  $\tau_{EE} > 1$ , the PV  
 177 integration increases energy exchanges with the grid.

178 *2.3.2. Objective 2: Minimization of the reduced load variations*

179 The second objective is minimizing the ramp rates (RR). Ramp rates are sudden variations of  
 180 power on the grid. In the case of a building with PV panels, ramp rates correspond to variations  
 181 in the reduced load  $L_r$ . The RR is defined here as

$$RR(t) = \frac{L_r(t + \Delta t) - L_r(t)}{\Delta t} \quad (9)$$

182 and the objective will be to minimize the standard deviation of the RR,  $\sigma(RR)$ .

183 Similarly to objective 1, an indicator is defined to assess the improvement in the RR attenua-  
 184 tions. It is defined as

$$\tau_{RR} = \frac{\sigma(RR)}{\sigma\left(\frac{L(t+\Delta t) - L(t)}{\Delta t}\right)}. \quad (10)$$

185 A value of  $\tau_{RR}$  smaller than 1 means that the variations in the ramp rates decrease compared to  
 186 the case in which the same building does not have PV installation.

187 *2.3.3. Objective 3: Maximization of the economic benefits*

188 There are several metrics to quantify the economic benefits from PV systems [14, 34]. Among  
 189 them, the Net Present Value,  $NPV$  is the most widely [14]. It is defined as

$$NPV = B_L - C_L \quad (11)$$

190 where  $B_L$  and  $C_L$  respectively correspond to benefits and costs of the system during its lifetime  
 191  $L = 30$  years [14].



192 Benefits are calculated as [14]

$$B_L = S_0 + \sum_{k=1}^L \frac{E_{sc}p_r + E_e p_w}{(1+d)^k}, \quad (12)$$

193 where  $d$  is the discount rate, evaluated by Sommerfeldt and Madani [14] at 3%.  $S_0$  corresponds  
194 to subsidies,  $E_{sc}$  is the self-consumed energy (defined in eq.2) and therefore  $E_{sc}p_r$  corresponds  
195 to savings made by deferring purchases to the grid at the retail price  $p_r$ .  $E_e$  corresponds to the  
196 excess production of energy (defined in eq.3), sold to the market at the wholesale price  $p_w$ .

197 Costs are calculated as

$$C_L = I_0 + \sum_{k=1}^L \frac{OM_k}{(1+d)^k}. \quad (13)$$

198 The yearly operations and maintenance costs at year  $k$  ( $OM_k$ ) are evaluated at a fixed cost of 1%  
199 of the investment  $I_0$  [14], the latter being the sum of the investment in the panels installed on the  
200 roof  $I_R$  and on the façades  $I_F$ .

#### 201 2.4. Case study: French part of the Great Geneva

202 The present work is conducted as part of a French-Swiss project in the cross-border region of  
203 the Great Geneva. The case of a building on the French part of the Great Geneva will be studied  
204 here.

##### 205 2.4.1. Climate and weather

206 Great Geneva has a continental weather and a latitude of 46.2°. Continental climate appears  
207 in more than half of Europe and large regions in Asia and North America. Moreover, the latitude  
208 of these regions remains close to those of Geneva. For these reasons, some the results of the  
209 present study can be generalized for a much wider region than only the Great-Geneva region.

210 The weather conditions for a standard year (.epw file) were taken from Geneva weather station,  
211 located at Geneva airport. This weather station is located at the French-Swiss border so that  
212 the weather file can be used for French or Swiss conditions.

##### 213 2.4.2. PV production and building load

214 The PV production throughout the year was simulated with the help of EnergyPlus software  
215 for the estimation of incident solar radiation on each outdoor surface.

216 For the load curve, real consumption profile were used. Referred to as  $l(t)$ , they correspond  
217 to a non-dimensional aggregation of the consumption profiles in French Geneva. Therefore, the  
218 consumption of the building is defined here as

$$L(t) = K \times A_T \times l(t) \quad (14)$$

219 where  $K$  ( $kWh/(m^2.y)$ ) is the annual energy consumption density of the building and  $A_T = S_r \times$   
220  $N_f$  is the total living area. The time step for both the PV production and the building energy  
221 consumption is  $\Delta t = 10$  min.

222 Except when explicitly mentioned in section(3.2), in the rest of the manuscript the focus  
223 will be on the tertiary building load profile. One of the main reasons is that tertiary building  
224 are particularly interesting for PV self-consumption as the energy consumed by these building is  
225 higher during daytime, when there is PV production.

226 2.4.3. Economical data

227 In order to calculate the economic parameters defined in section 2.3.3,  $p_r$  is taken at 15 cts/kWh,  
 228 the French mean price in 2020.  $p_w$  and  $S_0$  depend on the total installed capacity as indicated in  
 229 Table 1.

Total PV capacity (kWp)	[0-3]	]3-9]	]9-36]	]36-100]	> 100
$p_w$ in cts/kWh	10	10	6	6	0
$S_0$ in €/kWp	390	290	180	90	0

Table 1: Subsidies and retail prices for self-consumption in France in September 2020

230 In the French context,  $S_0$  and  $p_w$  only depends on the installation size and the date the PV  
 231 installation is connected to the grid (here prices are for April 2020). A contract with the energy  
 232 provider prevents  $p_w$  to change over the lifetime of the system. Nevertheless, it is very likely  
 233 for the price of energy, and therefore  $p_r$  to change in the coming years. It is extremely difficult  
 234 to predict but it is very likely that this price will increase which should make self-consumption  
 235 more profitable

236  $I_R$  can be easily estimated from the French market prices [35] as was reported in Figure 2.  
 237 To approximate these data, two power-law interpolation curves were used between 5 and 100  
 238 kWp and between 100 and 800 kWp respectively. As for  $I_F$ , it is much more difficult to estimate  
 239 because of the lack of economic data about façades. In the present work, this cost is regarded  
 240 as following a law similar to that of  $I_R$  multiplied by a factor of 1.5, which is coherent with  
 241 previously used economic estimations [16]

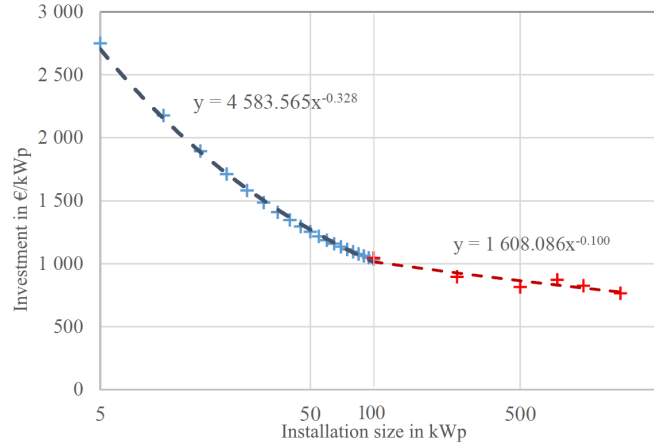


Figure 2: Investment costs for roof mounted PV system  $I_R$  as a function of the total installed capacity. Symbols represents average market prices and dotted line represent interpolation of these data. Two interpolation curves were used, a power law in the range [5,100] and a linear interpolation for installed capacity greater than 100 kWp.

242 2.5. Optimization functions and variables

243 The three objectives that needs to be optimized are:

- 244 • Obj.1 -  $E_{grid}$  (eq.7),

- 245 • Obj.2 -  $\sigma(RR)$  (eq.9),
- 246 • Obj.3 - the NPV (eq.11).

247 In these optimization problems, the areas that PV systems cover on each of the surfaces are  
 248 optimized. In other words, the variables of the optimization problems are  $S_{PV,i}$ ,  $i \in \{r, e, w, s\}$ .  
 249 The variables are therefore bounded by the absence of PV panels and by  $S_{u,i}$ ,  $i \in \{r, e, w, s\}$ ,  
 250 the maximum usable areas on each surface. In Obj.1,  $E_{grid}$  depends on  $P(t)$  which is directly  
 251 proportional to  $S_{PV,i}$  (see eq.5). From eq.9 it is also straightforward how  $\sigma(RR)$  depends on  $S_{PV,i}$ .  
 252 Finally, regarding Obj.3, the NPV depends on  $B_L$  which depends on  $E_{sc}$  and  $E_e$ , both dependent  
 253 on  $P(t)$  and therefore on  $S_{PV,i}$ . Furthermore, as was presented in section 2.4.3, the economic  
 254 parameters  $S_0$ ,  $I_0$ ,  $p_w$  and  $OM_k$  also depends on the total size of the PV installation and therefore  
 255 on  $S_{PV,i}$ .

256 Therefore it appears that for each objective  $q = 1, 2, 3$  the optimization problem can be simply  
 257 written as

$$\min_{S_{PV,i}} \left\{ f_q(S_{PV,i}), S_{PV,i} \in [0, S_{u,i}] \right\}, i \in \{r, e, w, s\}. \quad (15)$$

258 The objective functions  $f_1$  and  $f_2$  are respectively  $E_{grid}$  and  $\sigma(RR)$  whereas  $f_3 = -NPV$ .  
 259 Indeed, the minimization of  $f_3$  corresponds to the maximization of  $NPV$ . In order to minimize  
 260 the objective functions, the ‘fmincon’ optimization solver from the Matlab environment is used  
 261 [36]. ‘fmincon’ algorithm uses gradient based methods and can be used with continuous multi-  
 262 variable objective function.

263 It can be noted that  $I_R$ ,  $I_F$ ,  $p_w$  and  $S_0$ , are non-continuous piecewise defined functions, which  
 264 make the direct use of the ‘fmincon’ optimization solver impossible. In that case, the optimiza-  
 265 tion is made on each sub-interval on which the objective function is continuous. Here it corre-  
 266 sponds to the intervals defined by the PV total installed capacity ranging in  $[0,3]$ ,  $[3,9]$ ,  $[9,36]$ ,  
 267  $[36,100]$  and  $[100,+\infty]$ . It therefore provides five local minima. Then the global minimum is  
 268 simply taken as the minimum of the local minima.

269 Finally, the objective functions are minimized considering the load and production profile of  
 270 an entire year.

### 271 3. Results

272 The next section presents the results of the optimization according to these various param-  
 273 eters. First the influence of the objective on the optimal integration is presented. Then the  
 274 influence of the building load profiles is looked at. Finally, a parametric study of the impact size  
 275 and energy consumption of the building is presented.

#### 276 3.1. Optimal PV integration strategies depending on the objective

277 Different strategies, all linked to self-consumption, may lead to different PV integrations.  
 278 This is illustrated in Figure 3, where the optimal integration for each of the objectives is pre-  
 279 sented. In this figure, all the considered façades and the roofs are shown in unfolded view. The  
 280 colour shades indicate the percentage of the usable surface that is covered by PV panels.

281 It first appears that the optimal PV integrations are fundamentally different depending on  
 282 the objective. In the case of the low-rise building, Obj.1 favors vertical façades and the roof is  
 283 not entirely equipped whereas the opposite integration is obtained for the third objective. This

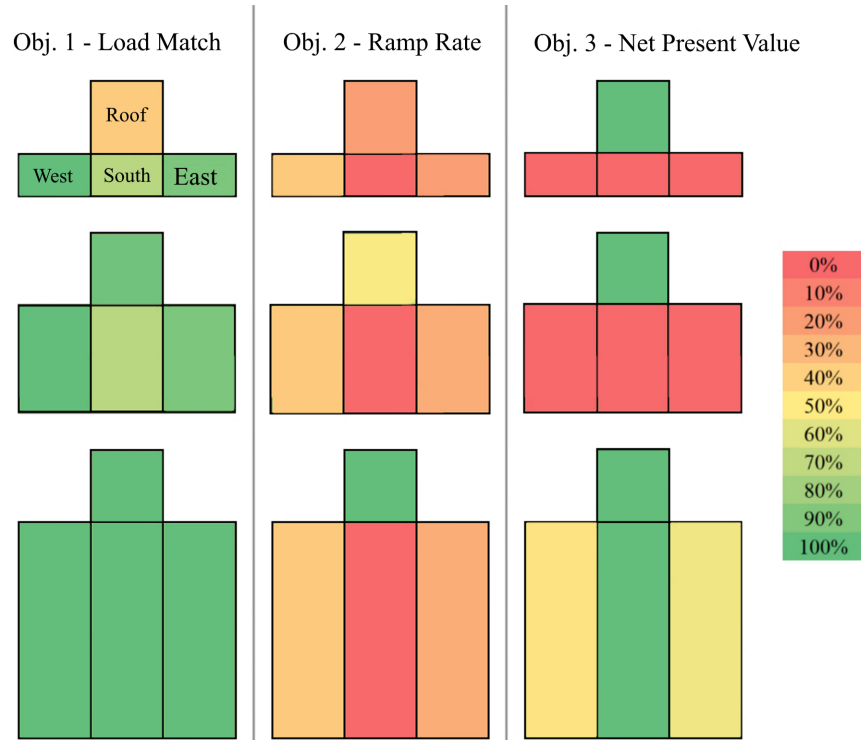


Figure 3: Unfolded view of the roof, east, south and west façades of the buildings under study. From top to bottom: low-rise, mid-rise and high-rise buildings. From left to right: Obj.1 , Obj.2 and Obj. 3. The colours indicate the PV coverage rate of the surfaces (Red: no panels on the surface. Dark green: the entire available surface is used). Case of an annual surface consumption of  $K = 50 \text{ kWh}/(\text{m}^2 \cdot \text{y})$ .

284 derives from the economy of scale and the subsidy scheme. Indeed, for the low-rise and mid-  
 285 rise buildings, the inclusion of PV on the vertical façades is not profitable whereas it becomes  
 286 profitable for the high-rise building. However, the west and east façades are not fully covered.  
 287 This is because the installed capacity reaches 100 kWp, a threshold after no more subsidies are  
 288 granted (see table 1). The optimal integration according to Obj. 2 consists in a small coverage of  
 289 the east and west façades whereas the roof is entirely covered only for the highest building.

290 In order to better understand the results of the optimizations, it is possible to plot, on the same  
 291 graph, the PV production for each façade and the building load. This was done in Figure 4 for the  
 292 low-rise building with an annual consumption of  $K = 50 \text{ kWh}/(\text{m}^2 \cdot \text{y})$ . The low-rise building is  
 293 chosen here because the optimal integration have strong differences. In this figure, the production  
 294 of each façade  $P_k$ , the total PV production  $P$  and the building  $L$  are plotted on the same chart.  
 295 To better visualize the load match during the sunny hours, the 'lack' of energy - when the PV  
 296 production is lower than the building load - has been coloured in blue, and the 'excess' - when  
 297 total PV production exceeds the building load - have been coloured in orange.

298 It can be seen that in the case of Obj.1, east and west façades are almost fully covered, which  
 299 produces a 'double hump' in the production profile. This characteristic makes it possible to better  
 300 match the load of the building which also has a 'double hump'. In the case of Obj. 3, the PV

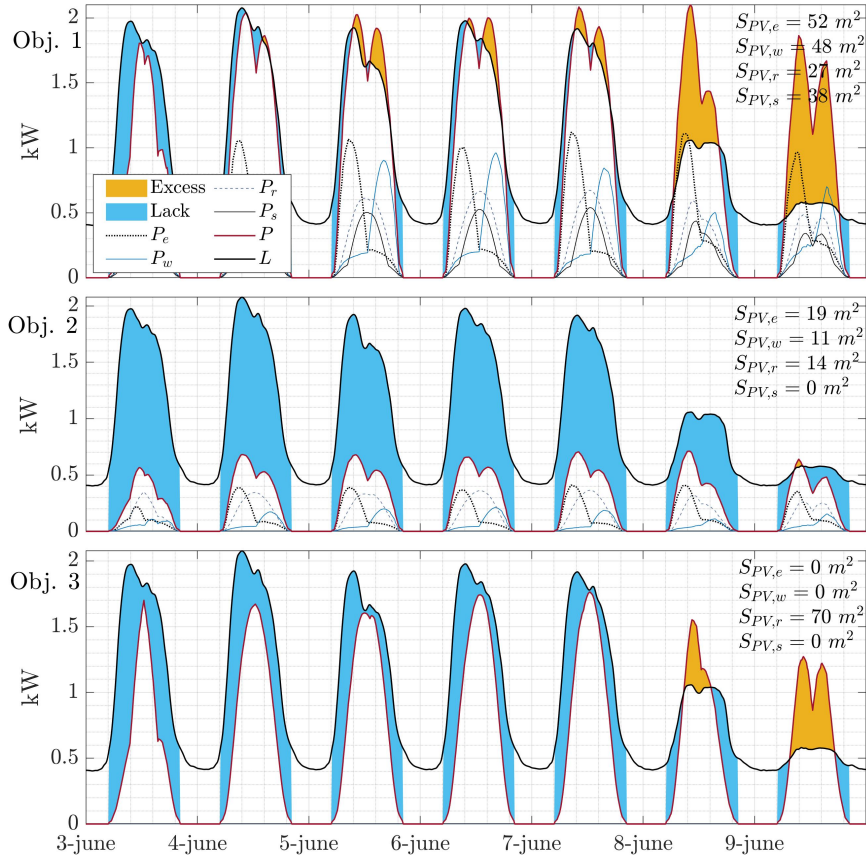


Figure 4: Production (red) and load (black) curves for the low-rise building and for the three optimal PV integration (Obj. 1 to 3). The blue and orange areas correspond to deficits and excesses of production compared to consumption. The production curves for each façade are also plotted, but only visible for objectives 1 and 2 (for objective 3 the total production is equal to that of the roof, the others being zero).

301 production has the classic bell shape of PV production and covers a lot of energy needs in the  
 302 selected week. Finally, with Obj. 2, energy production is low compared to consumption. The  
 303 explanation is that here, the PV integration guarantees that the production ramps, that mainly  
 304 occur in the early morning and at the end of the day, correspond to the ramps in the building  
 305 load.

### 306 3.2. Influence of the load profile

307 Another factor that may influence the optimal integration of PV is the load profiles of the  
 308 building. Indeed, the load profile shape is a key variable in the calculation of the three objective  
 309 functions.

310 In Figure 5, the load and consumption curves of the low-rise building are plotted for a typical  
 311 week of June, for three different load profiles and integration strategies. For Obj.1, the optimal  
 312 PV configuration favors the vertical east and west surfaces. The south surface is also favored  
 313 compared to the roof which is almost not used in the case of the residential load. This is because,

314 under the considered latitude, the PV production of the southern façade has less seasonal vari-  
 315 ations than that of roof. Given that the building load has low seasonal variations, it is better to  
 316 reduce seasonal variations in the PV production by using the south façade.

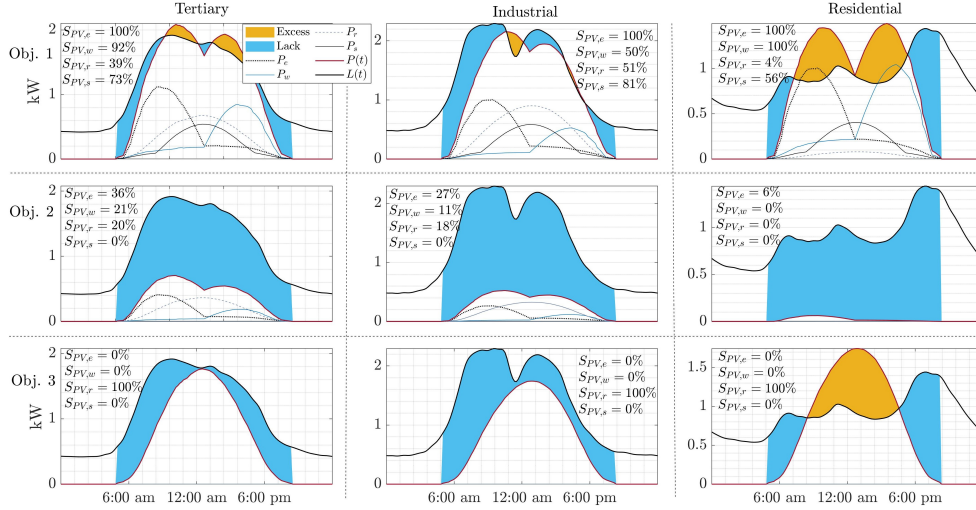


Figure 5: Production (red) and load (black) curves for the low-rise building. The production curves for each façade are also plotted. The blue and orange areas correspond to deficits and excesses of production compared to consumption. Typical weekday in June. From top to bottom : Obj. 1 to 3. From left to right: Tertiary, Industrial and Residential load profiles.

317 The optimal configurations, according to Obj.2, are similar for the industrial and tertiary  
 318 loads. In these cases, there is a low coverage rate of the roof, west and east façades and no use  
 319 of the southern façade. However, for the residential load, almost no PV should be integrated.  
 320 The reason is that the residential load have no ramps that coincide with the PV production and  
 321 therefore it is not possible to reduce the ramp rates in the reduced load. Finally, for Obj.3, the  
 322 optimal configuration is the same for all the load profiles, the roof being entirely covered and the  
 323 façades unused.

324 To sum up, for the considered building (low-rise,  $K = 50kWh/(m^2.y)$ ), the load profile of  
 325 the building has less influence on the optimal PV configuration than the optimization objective.  
 326 Whereas façades appear to be better in order to reduce energy exchanges with the grid (Obj. 1),  
 327 they are not interesting in order to reach maximum profitability.

328 It is important to note that the three load profiles that have been used here correspond to  
 329 aggregation of a wide range of loads. Despite the fact that they are representative of the tertiary,  
 330 industrial and residential load profiles, there is in fact more diversity in the shapes of the load  
 331 profile and consequently, in the corresponding optimal PV integrations.

### 332 3.3. Parametric Study

333 In order to keep investigating the optimal PV configurations, it is necessary to assess the  
 334 influence of fundamental building parameters which are their sizes and their consumption. In the  
 335 present case, to modify the building size, the number of floors  $N_f$  will be changed. The energy  
 336 consumption of the building will be changed by varying the electrical consumption density  $K$  in

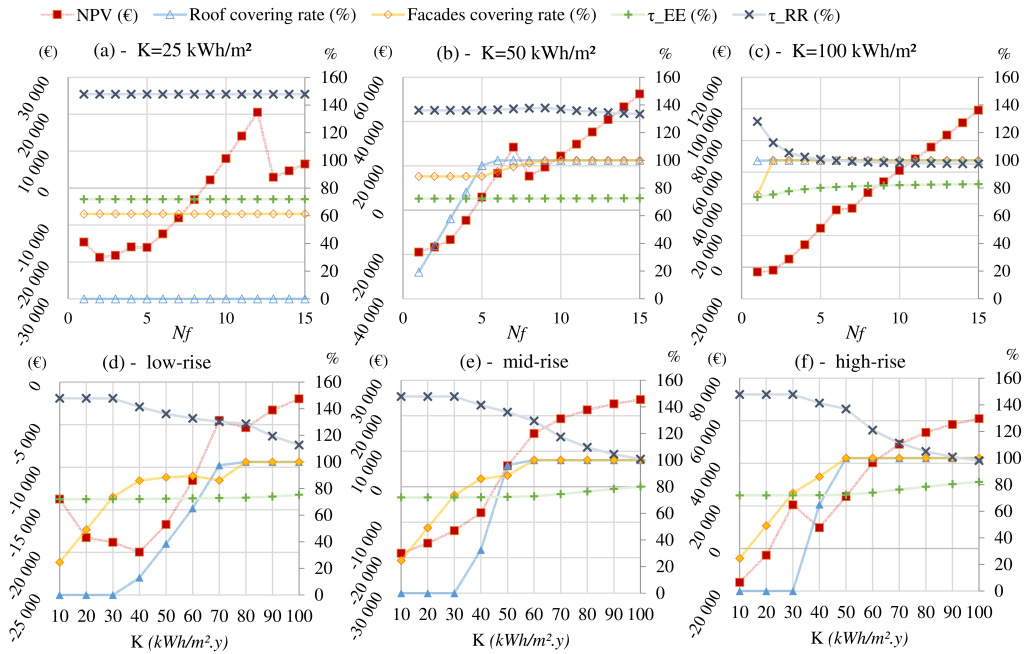


Figure 6: Optimal configuration according to Obj. 1: Minimizing the energy exchanges with the grid. For each  $x$ -value, the PV integration is optimized according to Obj.1. Evolution of the roof coverage (light blue triangle) and the façades coverage (orange diamond). They are expressed in % of the total usable surface, and their values is read on the right vertical axis. The three optimization indicators are also indicated: The NPV values (in €) can be read on the left vertical axis whereas the values of the energy exchange indicator  $\tau_{EE}$  and the ramp rate indicator  $\tau_{RR}$  can be read in % on the right axis . (a)  $K=25 \text{ kWh/m}^2/\text{y}$ , (b)  $K=50 \text{ kWh/m}^2/\text{y}$ , (c)  $K=100 \text{ kWh/m}^2/\text{y}$ , (d) low-rise building, (e) mid-rise building, (f) high-rise building.

337 ( $\text{kWh}/(\text{m}^2 \cdot \text{y})$ ). Note that, as was mentioned in section 2.4.2, in the remaining of the paper the  
 338 tertiary building load will be used.

339 The parametric studies will be conducted for each parameter independently so that when  $N_f$   
 340 varies,  $K$  remain constant and inversely.

341 Different consumption densities of electrical energy will be considered here,  $K = 25, 50$   
 342 and  $100 \text{ kWh}/(\text{m}^2 \cdot \text{y})$ .  $K = 50 \text{ kWh}/(\text{m}^2 \cdot \text{y})$  corresponds to the consumption of a new efficient  
 343 building according to French regulation and only using electrical energy.  $K = 25 \text{ kWh}/(\text{m}^2 \cdot \text{y})$   
 344 could correspond to a building that is using electrical energy in addition to another source of  
 345 energy.

346 In the following sections, the influence of these parameters will be investigated for each of  
 347 the optimization objectives.

### 348 3.3.1. Parametric study - Obj.1

349 A parametric study of the influence of the height of the building and its density of energy  
 350 consumption on the optimal PV configuration is presented for Obj.1 in Figure 6. In this figure,  
 351 six graphs are presented. On each graph, the NPV is read on the left vertical axis while the

352 energy exchange indicator  $\tau_{EE}$  and the ramp rate indicator  $\tau_{RR}$  can be read in % on the right axis.  
353 The coverage rate of roofs and façades, defined as the percentage of the usable surface covered,  
354 can also be read (in %) on the right axis.

355 In Figure 6 (a), (b) and (c), the building height evolved by changing the number of floors  
356 ( $N_f$ ) while keeping the energy consumption density constant, respectively (a)  $K=25$ , (b)  $K=50$   
357 and (c)  $K=100 \text{ kWh/m}^2/\text{y}$ . As was presented in section 2.1, one floor is 3 m high. Moreover, as  
358 the building gets higher, the livable surface also increases and with it the total energy consumed.

359 It first appears that the role of PV on surface is predominant here. Indeed, for each case,  
360 façades are covered in priority for smaller buildings or buildings with low energy consumption  
361 density  $K$ . However, as the size increases, both roofs and façades are used at their full potential  
362 (100% covering rate). The only exception is for building  $K=25 \text{ kWh/m}^2/\text{y}$  for which only façades  
363 are used, regardless of the building size.

364 Regarding the energy exchange indicator  $\tau_{EE}$ , the one which is optimized here, it appears  
365 that its values remain relatively constant through the whole parametric study with percentage  
366 around 70% for low-mid values of  $K$  and  $N_f$  and values around 80% for higher buildings with  
367 high consumption densities.

368 In other words, it means that here, the PV configuration reduces the energy exchanges of a  
369 building with the grid by up to 30%.

370 It should also be noted that the NPV is negative for the small values of  $K$  and  $N_f$  meaning  
371 that the PV systems are not economically profitable in these cases. The peak that can be observed  
372 in the NPV in graphs (a), (b), (d) and (f) are due to the subsidies scheme (section 2.4.3), that is  
373 decreased as the total capacity increases and stops above 100 kWp of PV capacity installed.

374 Finally, the ramp rate indicator  $\tau_{RR}$  has relatively high values around 150% except for high-  
375 rise buildings or buildings with high consumption for which the value drops to nearly 100%.  
376 This means that, when the configuration is optimum according to Obj. 1, the occurrence and  
377 intensity of the ramp rates significantly increases compared to a building without PV panels.

378 It can also be noted that except for the low-rise building in (a), the roof and façades reach their  
379 maximum capacity for high values of  $K$  and  $N_f$ . This means that, in these cases, the optimum  
380 configuration also corresponds to the maximum PV production.

### 381 3.3.2. Parametric study - Obj.2

382 Figure 7 is similar to Figure 6 except that this time, the PV integration is optimal according  
383 to Obj.2, which is the minimization of the ramp rates variations.

384 From this parametric study, it appears that the façades and roof covering rate varies almost  
385 linearly with the energy consumption density. The maximum PV capacity of the building is never  
386 reached in these cases. From the linear trends in (d) (e) and (f), we could expect the full covering  
387 of the façade to be reached at once, but this would occur for buildings with much higher energy  
388 consumption density.

389 Regarding the ramp rate indicator  $\tau_{RR}$ , optimized here, its value remains equal to 91%, in-  
390 dependently on the building size and consumption. Interestingly enough, the energy exchange  
391 indicator  $\tau_{EE}$  is also constant with a value of 90%. This means that for any of the size or con-  
392 sumption level investigated here, there is a PV configuration, which reduces the ramp rate vari-  
393 ations of the building equipped with PV by up to 9% while including the energy exchanges by  
394 nearly 10%.

395 However, it can be seen on the NPV evolution that, the PV configuration is only profitable  
396 for the high energy consumption density (c) or the high-rise building (f).



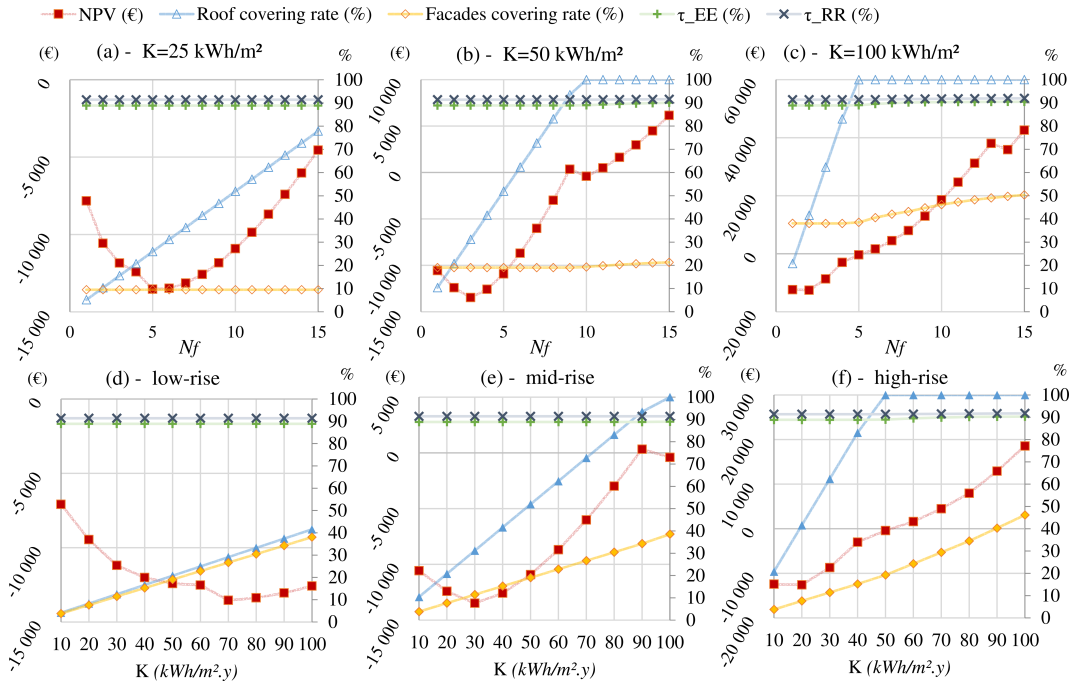


Figure 7: Similar as in Fig.6, (a)  $K=25 \text{ kWh/m}^2/\text{y}$ , (b)  $K=50 \text{ kWh/m}^2/\text{y}$ , (c)  $K=100 \text{ kWh/m}^2/\text{y}$ , (d) low-rise building, (e) mid-rise building, (f) high-rise building, for each x-value, the PV integration is optimized according to Obj.2 (RR)

### 3.3.3. Parametric study - Obj.3

Figure 8 is similar to Figure 6 except that this time the PV integration is optimal according to Obj.3, maximizing the NPV.

In this case, the roof is covered, almost at its full capacity even for the lowest building height and consumption. Then, as soon as the building is high enough for the vertical surfaces to reach a PV capacity of 100 kWp, façades start to be covered. It is very interesting to note in (b), (c) and (e) that the façade coverage jumps from 0% to 100% at once. This implies very high sensitivity of the optimal façade coverage rate to the building parameters. In each case, the NPV increases with the size of the building and its consumption density. However, in (a) and (b), it can be seen that the NPV reaches a plateau which stops as soon as façade integration becomes profitable enough to increase the NPV.

Here, the general trend is opposite to that observed for Obj.1. Indeed, in this case, roofs are first equipped up to their full potential for low-mid values of  $N_f$  and  $K$ , and then the façades are covered. This could be expected, given that façade integration is more expensive in terms of initial investment, and globally less productive in terms of energy production. However, it should be noted that for highest values of  $N_f$  and  $K$ , the roofs and façades are fully covered. This was also the case for the optimal configuration according to Obj.1 (see section 3.3.1). In other words, for high values of  $N_f$  and  $K$ , the covering the entire surfaces with PV corresponds to the optimal configuration for both Obj. 1 and Obj. 3.

Finally, here, the energy exchange indicator  $\tau_{EE}$  remains in the range of 80% to 100%, which means that all the optimal configurations according to Obj. 3 are also beneficial when considering

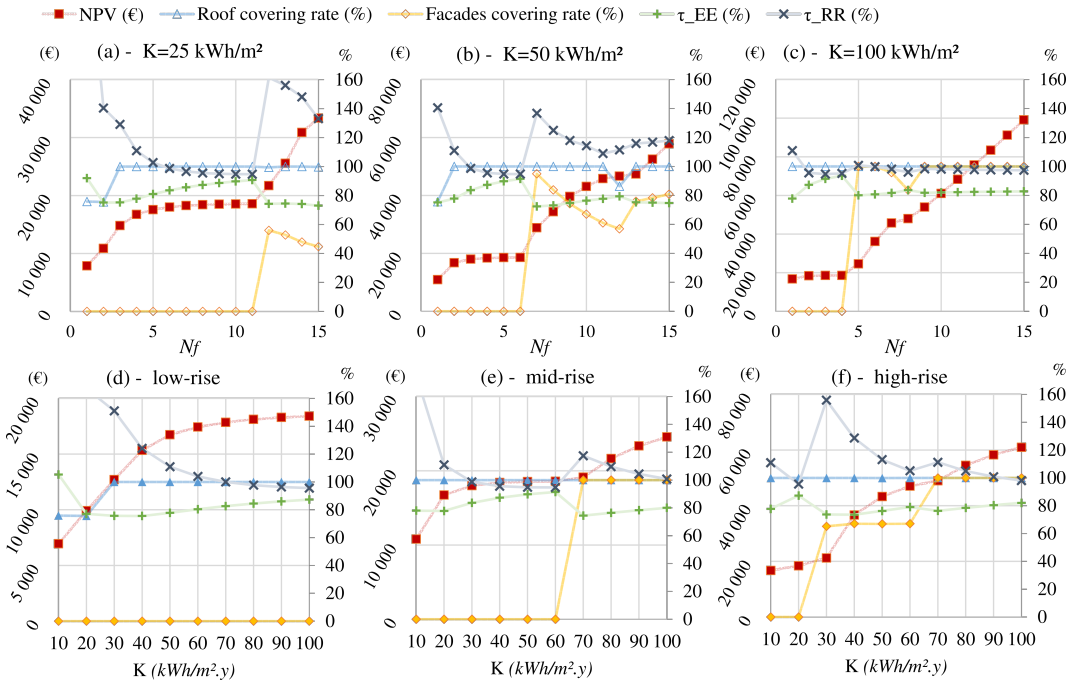


Figure 8: Similar as in Fig.8, (a)  $K=25 \text{ kWh/m}^2/\text{y}$ , (b)  $K=50 \text{ kWh/m}^2/\text{y}$ , (c)  $K=100 \text{ kWh/m}^2/\text{y}$ , (d) low-rise building, (e) mid-rise building, (f) high-rise building, for each x-value, the PV integration is optimized according to Obj.3 (NPV)

418 the energy exchanges with grid.

#### 419 4. Discussion and conclusion

420 In the present paper, optimization of the integration of PV on the roofs and façades of build-  
 421 ings is achieved based on different objectives related to self-consumption strategies. The first  
 422 objective aims to minimize the energy exchanges with the grid. The second aims to minimize  
 423 the reduced-load variations, also called ramp-rates (RR). The third objective is economic and  
 424 corresponds to a maximization of Net Present Value (NPV). The case of France is investigated,  
 425 and meteorological as well as economic inputs from France are considered.

426 It appears that most of the time, different self-consumption goals lead to different optimal  
 427 PV configurations. Indeed, for low and mid-rise buildings or buildings with low or medium  
 428 electrical energy consumption, the optimal configurations according to Obj.1 prioritize the uses  
 429 of the façades whereas roofs are prioritized when Obj. 3 is pursued. However, for high-rise  
 430 buildings or buildings with high energy consumption, the differences vanish for Obj.1 and 3,  
 431 once the full coverage capacity of the roof and the façade is reached. In other words, for these  
 432 buildings the PV configuration minimizes energy exchanges with the grid while maximizing  
 433 profitability.

434 When the power fluctuations are minimized (Obj.2), the surfaces of the buildings are most  
 435 of the time only partially covered, the maximum covering rate being reached for the highest  
 436 buildings and the highest energy consumption density.

437 The main observations and conclusions from the present works are:

- 438 • Different objectives linked to self-consumption lead to different PV configurations espe-  
439 cially for low and mid-rise buildings with low energy consumption levels.
- 440 • The use of all the surface of the building (roof and façades) is crucial in order to better in-  
441 tegrate solar energy. Façades are the most relevant in order to minimize energy exchanges  
442 with the grid, but they also become economically profitable for higher rise or more energy-  
443 consuming buildings.
- 444 • At the scale of a single building, minimizing the RR (Obj.2) leads to a rather low coverage  
445 of the roof and façades compared to other objectives.
- 446 • Optimal PV integration can reduce the energy exchanges with the grid of a building  
447 equipped with PV system by up to 30%.
- 448 • An adequate PV integration can reduce the load variation of a building equipped with PV  
449 by up to 9%.

450 From these results, several policy recommendations can be made. First of all, self-consumption  
451 has several co-benefits, which are economic as well as energetic (e.g., reduced grid energy con-  
452 sumption and power variations). Therefore, policies promoting self-consumption must be pur-  
453 sued. The current economic context and pricing schemes render the use of façades for PV energy  
454 production not economically profitable for small scale installations. However, the results of the  
455 present work demonstrate that the use of facades, even for small buildings, is significantly ben-  
456 efcial to the reduction of energy stress on the grid. It is also very likely that this 'profitability  
457 loss' is only a matter of scale. Indeed, the use of façades is likely to be not the most profitable so-  
458 lution for the owners of small buildings. However, considering a wider scale (regional/national),  
459 the use of façades will decrease the stress on the energy grid which, at last, will corresponds to  
460 energetic and economic benefits for the grid manager (who is a public actor in France). It will  
461 also allow a wider integration of renewable energy. Therefore, the subsidies and pricing schemes  
462 could evolve in order could be tailored to favor the use of the façades.

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