Multi-occupancy buildings as micro-grids: an asset for integrating photovoltaics in power systems

*CSEM SA, Rue Jaquet-Droz 1, 2002 Neuchâtel, Switzerland (vincenzo.musolino@csem.ch)

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Abstract

Distributed renewable energy sources (RES), such as photovoltaic systems (PV), can contribute to a reduction in the power quality in distribution grids due to higher power oscillations both in absorption and generation. In this work, by means of a statistical approach, the quality of supply at the point of common connection is evaluated for different PV sizes and also for different levels of aggregated loads sharing a single PV installation as can happen in multi-occupancy building.

The role of incentive schemes in Switzerland and UK in driving the choice for the installation of a specific PV size is evaluated.

1 Introduction

Renewable energy sources (RES) have experienced in the last decade the largest growth when compared to the traditional fuel resources: 81% increase between 2002 and 2012 in Europe for primary energy production [1], [2]. The use of renewable energy sources is seen as a key element in the energy policy of many countries. Yet major challenges in RES penetration are related to the instability they can introduce in the power grids due to the high variability and randomness of the generation profile associated to weather conditions, especially for wind and PV installations.

With the focus on PV systems the attention will be placed on the expected dispatching profile which is difficult to evaluate due to the unpredictability of loads and generation. The power profile evaluation at the point of common connection (PCC) requires making reasonable assumptions on the possible profiles. In particular load profiles are strictly dependent on factors such as the house extension, geographical location, period of the year and specific customer habits, while the PV generation is mainly dependent on the configuration of the PV field, actual irradiation and weather condition.

2 Equivalent power profile at the point of common connection (PCC)

Evaluating the equivalent power profile at the PCC, where different loads and the PV field are connected, requires making reasonable assumptions on the possible power profiles. In particular load profiles are strictly dependent on factors such as the house extension, geographical location, period of the year and specific customer habits, while the PV generation is mainly dependent on the configuration of the PV field, actual irradiation and weather condition.

2.1 Residential building load profile

Each load dataset is made of one-year load profile data based on one-hour samples, and they are available for all Typical Meteorological Year (TMY3) locations in the United States [7]. This work is focused on the load consumption of residential buildings based on the “Building America House
Simulation Protocols” [8]. Among the simulated profiles the “Base Load model” has been used [9], referring to building structures with a living surface of about 200 m², 3 bedrooms and 1.4 bathrooms on average [9]. The simulated loads are split in 14 categories including electric and heating loads. Among the different categories we considered:

1. Total – electric load
2. Total – heating load
3. Total – electric + heating

With the last category we want to take into account the total equivalent load in case of using electricity for both pure electric loads and heating purposes. Considering the 936 simulated loads profiles, the one-hour averages are reported in Figure 2, where the inset shows the average of one-hour samples.

![Figure 2: Residential houses: average annual load power profile considering the Base Load model [9].](image)

An important point is that for each hour the standard deviation of the power sample is quite large, as shown in Figure 3. That means that an average profile cannot be considered a priori as reference, but a statistical approach, instead, can give more realistic results. In this work the latter approach will be used and in particular the evaluation of the probability distribution function of the one-hour samples and how it changes as function of the PV size installation and house loads aggregation.

![Figure 3: Hourly standard deviation of the power samples for residential houses considering the Base Load model [9].](image)

The average power and annual energy demand corresponding to the load under consideration are reported in Table 1.

<table>
<thead>
<tr>
<th>Load type</th>
<th>Average Power (kW)</th>
<th>Average Energy (MWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>1.28</td>
<td>11.2</td>
</tr>
<tr>
<td>Heating</td>
<td>2.35</td>
<td>20.6</td>
</tr>
<tr>
<td>Total</td>
<td>3.6</td>
<td>31.5</td>
</tr>
</tbody>
</table>

Table 1: Average energy demand for the residential houses considering the Base Load model [9].

2.2 PV installation

The simulated one-hour-based power outputs of the PV installations include the real performance of selected PV modules and power inverters. The equivalent PV field sun irradiation as a function of the weather conditions, PV field azimuth and tilt module angle are also taken into account. For our purpose we have considered an installation based on Nexpower® 170 Wp solar modules and a centralized Sunny Boy® series inverter manufactured by SMA. The size of the PV installation ranges from 1 kWp up to 100 kWp and according to the inverter selection nominal power changes. For all cases the PV installation is located in Neuchâtel (CH).

![Figure 4: Reference PV power output considering 1kWp installation in Neuchâtel (CH) for a PV field of 0° azimuth angle and 30° tilt angle.](image)

In the following sections results concerning the integration of PV systems in collective houses will be presented. In particular two aspects will be discussed: the first one concerns the evaluation of technical benefits related to the installation of a shared PV installation in a collective house, while the second one is about evaluating the impact of the incentive scheme in driving the investment in PV installations.
3 Technical Analysis

In a first step power profiles of the single house are taken into consideration as references. Due to the large number of available profiles, the information is aggregated in Error! Reference source not found. as probability density of the one-hour exchanged power at the PCC in the presence or absence of PV (3 kWp in size) and in the presence or absence of house aggregation at the same PCC.

The aggregated loads considered in the figures consist of the sum of up to 30 randomly selected house profiles. In these cases the size of the PV installation size is 30 times greater than the size considered for the single house, but for homogeneity in the exposition, all the reported values in and Error! Reference source not found. are scaled by a factor of 30.

Each coloured bar indicates the probability that a certain power value is exchanged with the grid. The profiles, one year each based on one-hour samples, show absorbed power as positive values as and injected power as negative values.

The first point to note is that the presence of PV reduces the frequency of the events with a power value of 0, which means that the utilization factor of the grid is increased due to the reduced probability to have no power exchanges. In addition the introduction of PV reduces the average of the exchanged power due to the presence of negative values of power exchanged with the grid.

Beside this the aggregation of “heating” and “total” loads contributes to further flattening the distribution of power values. This flattening does not appear for the pure electric loads. This difference is mainly due to the hypotheses used to build the simulated electric load power profiles, where a time shift among power profiles of different houses has not been considered.

For a quantitative analysis the average values and the standard deviation of the one-hour power values exchanged at the PCC have been collected in Table 2. From this table general lessons can be drawn:

- The load aggregation reduces the standard deviation of the one-hour-based power values exchanged at PCC by 2% to 8% for “heating” and “total” loads, while it increases for the “electric loads”
- The PV installation reduces the average power values exchanged with the grid the larger the size of the PV system.
- The standard deviation values tend to decrease by increasing the number of aggregated loads.

The standard deviation values in case of PV installation with power ratings between 3 kWp and 5 kWp are quite close to the values without PV installation.

As previously mentioned, the effect of load aggregation is negative for the pure electric load profiles, due to the fact that the simulated data don’t include a time shift between different profiles. However, even in this case, the introduction of a PV installation in the power range of 3 kWp reduces the standard deviation values by about 2% to 5% compared to the case without PV installations.

As a general rule, independently of the average power of the load considered, the lowest standard deviation values in case of PV installation are obtained for a PV size of 3 kWp.

Another technical aspect considered in this evaluation is the portion of energy directly self-consumed as a function of the PV size as shown on Figure 7. This fraction is nearly independent of whether the average of single profiles or aggregated data is considered. The evolution of the self-consumed fraction as a function of the PV size is also similar for the different types of loads, despite the fact that “electric” and “heating” loads are very different in shape and the average of the latter is about double the average power of the first one. This indicates similar shifting of the PV power profiles and loads.

![Figure 6: Probability density of net power exchanged at the PCC considering the total electric loads (Base Load model [9]). Data are shown for a single house and 30 aggregated ones with and without a PV system of 3 kWp in size.](image)

![Figure 5: Probability density of net power at the PCC considering the total heating loads (Base Load model [9]). Data are shown for a single house and 30 aggregated ones with and without a PV system of 3 kWp in size.](image)
### Table 2: Mean power and standard deviation expressed in kW of the 1-hour power values of the net power at the PCC considering different number of aggregated houses.

<table>
<thead>
<tr>
<th>PV size (kWp)</th>
<th>N° of houses</th>
<th>1/10/30</th>
<th>1.29</th>
<th>0.9</th>
<th>0.65</th>
<th>0.39</th>
<th>106.5%</th>
<th>114.7%</th>
<th>118.7%</th>
<th>120.3%</th>
<th>137.5%</th>
<th>143.6%</th>
<th>146.3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric loads</td>
<td>Mean power (kW)</td>
<td>1</td>
<td>0.22</td>
<td>0.32</td>
<td>0.43</td>
<td>0.56</td>
<td>0.23</td>
<td>0.36</td>
<td>0.52</td>
<td>0.68</td>
<td>120.3%</td>
<td>0.24</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>STD (kW)</td>
<td>10</td>
<td>0.23</td>
<td>106.5%</td>
<td>0.36</td>
<td>114.7%</td>
<td>0.52</td>
<td>118.7%</td>
<td>0.68</td>
<td>120.3%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>0.24</td>
<td>110.3%</td>
<td>0.44</td>
<td>137.5%</td>
<td>0.63</td>
<td>143.6%</td>
<td>0.82</td>
<td>146.3%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating loads</td>
<td>Mean power (kW)</td>
<td>1</td>
<td>0.82</td>
<td>0.86</td>
<td>0.91</td>
<td>0.97</td>
<td>0.73</td>
<td>0.83</td>
<td>0.89</td>
<td>0.95</td>
<td>98.3%</td>
<td>0.69</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>STD (kW)</td>
<td>10</td>
<td>0.73</td>
<td>88.9%</td>
<td>0.83</td>
<td>96.2%</td>
<td>0.89</td>
<td>97.3%</td>
<td>0.95</td>
<td>98.3%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>0.69</td>
<td>84.2%</td>
<td>0.82</td>
<td>95.2%</td>
<td>0.88</td>
<td>96.9%</td>
<td>0.95</td>
<td>98.4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total loads</td>
<td>Mean power (kW)</td>
<td>1</td>
<td>3.6</td>
<td>3.21</td>
<td>2.96</td>
<td>2.71</td>
<td>0.73</td>
<td>0.78</td>
<td>0.83</td>
<td>0.89</td>
<td>91.9%</td>
<td>0.69</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>STD (kW)</td>
<td>10</td>
<td>0.82</td>
<td>88.8%</td>
<td>0.87</td>
<td>91.7%</td>
<td>0.87</td>
<td>90.9%</td>
<td>0.89</td>
<td>91.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>0.69</td>
<td>84.4%</td>
<td>0.8</td>
<td>91.7%</td>
<td>0.85</td>
<td>93.4%</td>
<td>0.92</td>
<td>95.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: Average self-consumed energy fraction for different PV size installations considering 10 aggregated house load profiles according to [9].

### 4 Economic Analysis

Further to the above technical discussion, the aim in this section is to evaluate the economic impact of incentive schemes. In particular want to verify if PV systems whose size guarantees higher returns on investment also correspond to the best compromise from a technical point of view.

Among the different schemes the attention in this work is placed on the current photovoltaic incentives in Switzerland and the UK.

#### 4.1 Swiss photovoltaic incentive scheme

Two incentive schemes are currently active in Switzerland: feed-in remuneration and one-off investment grants.

The first instrument pays for PV electricity fed into the grid at generation cost, irrespective of market prices, while the second one encourages the installation of small photovoltaic systems by covering a maximum of 30% of the investment costs. The values and conditions of the two support mechanisms have been set in the updated administrative act on energy [10]. In particular, the PV feed-in remuneration lasts for a period of 20 years.

Our focus is only on the feed-in remuneration scheme which is mandatory for PV installations greater than 30 kWp and summarised on Table 3.

#### 4.2 UK photovoltaic feed in remuneration

The UK Government's Feed-In Tariffs scheme (FITs) pays for the generated electricity from a renewable or low-carbon source, whether the energy is used for self-consumption or exported to the grid. In addition, as in the Swiss case, savings are made on the electricity bill for the self-consumed fraction. In the UK scheme three incentive rates are defined [12]: higher, medium and lower.

The middle incentive rates considered in our simulations with an eligibility date between 1st April 2014 and 1st July 2014 are collected in Table 4.

Table 3: Values of feed-in remuneration in Switzerland for grid connected PV systems

<table>
<thead>
<tr>
<th>Nominal Power (kWp)</th>
<th>Remuneration (cCHF/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤30 kW</td>
<td>26.4</td>
</tr>
<tr>
<td>≥100 kW</td>
<td>22.0</td>
</tr>
</tbody>
</table>

Table 4: Values of feed-in tariffs in the UK for grid-connected PV systems with power rating in the range of 10 kWp to 150 kWp.
Two main differences with the Swiss scheme can be summarized:

- The incentive tariffs are updated quarterly
- In addition to the generation tariff, an export tariff is applied for each unit of energy exported back to the electricity grid

As for the Swiss scheme the guaranteed payment period is 20 years.

The comparison between the two incentive schemes is focused on grid-connected PV installations on multi-occupancy buildings with a level of aggregation of 10. This corresponds to our simulations to a PV rated power in the range of 30 kWp to 70 kWp. The corresponding system cost is 2200 CHF/kWp. For systems in the range of 3 kWp to 7 kWp, we assume a cost of 2800 CHF/kWp. The energy cost, instead, is the energy cost of a single house due to the fact that each single apartment in the multiple dwelling has a dedicated contract with the distributor. For the two countries this means an average cost of 0.29 CHF/kWh in Switzerland and 0.23 CHF/kWh in the UK. As previously, the results are shown scaled by a factor of 10 for easier comparison.

In Figure 8 the net present cost of electricity over a time horizon of 20 years is reported. This net cost takes into account the savings made by self-consumption of a fraction of PV-generated electricity, the cost of the PV installation and the revenues from the incentives. In addition an interest rate \( r_i \) of 3% and a discount rate \( r_d \) of 4% have been assumed. The latter also integrates the likely increase in electricity prices. The net present cost \( NPC \) is calculated as per Equation (1):

\[
NPC = PV_{field\_cost} + \sum_{t=0}^{\infty} \Delta Cost_{Energy} \left(\frac{1+r_i}{1+r_d}\right)^t - \text{Incentive} \left(\frac{1}{1+r_d}\right)^t
\]

(1)

Where:

\( \Delta Cost_{Energy} \) represents the amount of money saved for the energy not purchased from the distributor because self-produced by the PV field,

“Incentive” represents the sum of incentives proportional to the amount of net injected energy into the grid, for the Swiss scheme, or produced by the PV installation, for the UK scheme.

<table>
<thead>
<tr>
<th>Incentive Scheme</th>
<th>PV rated power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 kWp</td>
</tr>
<tr>
<td>Switzerland</td>
<td>7.3</td>
</tr>
<tr>
<td>UK</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Table 5: Payback time in years of the complete system considering 10 aggregated houses

The payback time in the different cases is reported in Table 5. The following conclusions can be drawn:

- Both schemes give better incentives for smaller PV sizes.
- The latter aspect is mainly due to the fact that, as indicated in Figure 7, smaller PV installations increase the percentage of the energy produced by the PV installation that can be self-consumed. Considering that feed-in tariffs in both countries are below retail electricity prices, it is clear that increasing self-consumption reduces the payback time of the PV investment. In particular the incentives for self-consumption are clearer in the Swiss scheme, while in the UK the presence of the export tariff still somehow incentivises PV energy producers to export energy. Yet even if one assumes an export tariff of 0 the UK incentive scheme is more attractive from an economic point of view.

In the case of multi-occupancy buildings the installation of a unique centralized PV system is characterized by larger nominal rated power. That means, when compared to single house PV installations, the possibility to have lower specific PV installed costs (20% less in our hypothesis). Despite lower incentive tariffs the payback time of PV installations in aggregated houses is, on average, 20% lower than for single houses as shown in Table 6.

Similar considerations are also valid for the other types of loads, previously named as “heating” and “total” loads; in these cases the payback times are further reduced due to the higher fraction of self-consumed energy.

![Figure 8: Net present electricity cost for the complete system considering 10 aggregated houses; solid lines: Swiss case, dotted lines: UK case.](image)

<table>
<thead>
<tr>
<th>Incentive Scheme</th>
<th>PV rated power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 kWp</td>
</tr>
<tr>
<td>Switzerland</td>
<td>8.7 (+19%)</td>
</tr>
<tr>
<td>UK</td>
<td>6.7 (+17%)</td>
</tr>
</tbody>
</table>

Table 6: Payback time in years of the complete system considering single-house profiles

5 Conclusion

In this work the integration of PV systems in multi-occupancy buildings in comparison with single houses has been addressed.

By means of a statistical approach it has been possible to evaluate a high number (936) of simulated residential load...
profiles according to the Base Load model developed by the OpenEI Community [9]. Pure electric loads and heating power profiles have been considered over a time horizon of one year with a time resolution of one hour. The same have been simulated for a PV installation ranging from 3 kW\textsubscript{p} to 70 kW\textsubscript{p} rated power.

The composition of different loads and generation profiles has allowed us to evaluate the power profile at the PCC with a resolution of one hour and in particular to evaluate the statistical power samples distribution. The case of a multi-occupancy building sharing the same PV installation has been simulated by aggregating the load profiles (in the range of 10 up to 30 profiles). The approach shows from a quantitative point of view that for \( n \) aggregated residential loads, a PV size of \( 3\cdot n \) kW\textsubscript{p} rated power is the limit to reach the lowest values of standard deviation of the power distribution samples at the PCC. The benefit of aggregation is in reducing the standard deviation by about 10%.

The economic analysis also shows that the incentive scheme tends to reward bigger PV installations. In case of multi-occupancy buildings the installation of PV systems in the range of \( 3\cdot n \) kW\textsubscript{p} produces the best results in terms of payback time of the investment.

As future work the attention will be placed on two aspects. The first one is using this approach with real, measured data profiles for which a larger time shift between power profiles is expected. The second one concerns the role of storage in further reducing the standard deviation of the power distribution at the PCC and its coordination with possible incentive schemes for a massive penetration in distribution grids.

References


