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Grid-connected photovoltaic power systems: Power value and capacity value of PV systems

Task V
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PVPS

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA PVPS
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Implementing Agreement on Photovoltaic Power Systems

TASK V
Grid Interconnection of Building Integrated
and Other Dispersed Photovoltaic Power Systems

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GRID-CONNECTED PHOTOVOLTAIC POWER SYSTEMS: POWER VALUE AND CAPACITY VALUE OF PV SYSTEMS

February 2002

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CONTENTS

Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its 23 member countries. The European Commission also participates in the work of the Agency.

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA, and since 1993 its participants have conducted various joint projects on the photovoltaic conversion of solar energy into electricity.
The members are: Australia, Austria, Canada, Denmark, European Commission, Finland, France, Germany, Israel, Italy, Japan, Korea, Mexico, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

This report has been prepared under the supervision of PVPS Task V by

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in co-operation with experts of the following countries:

Denmark, Japan, Mexico, Portugal an United Kingdom

and approved by the Executive Committee of the PVPS programme.

The report expresses as accurately as possible the international consensus of opinion on the subjects addressed.

Abstract and keywords

This report summarises the results of a study aimed to assess the benefits that may be obtained when distributed PV production systems are present in a LV grid. Basically, there are aspects that may be divided between those concerning the Power value and those related to the Capacity value.

Data obtained from simulations have confirmed that the more electric loads are in phase with PV production, the more power value and capacity value increase. This simple concept shows however great variation if different load pattern are taken into account.

Although the three cases-study considered do not cover all the possibilities of coupling between PV and loads, the results obtained show a good differentiation among users with PV production that lead to interesting conclusions.

Keywords: Photovoltaic power generation, Grid interconnection, Utility distribution system, PV inverters, Distributed power generation, Power value, Power capacity

Executive Summary

The power value of PV generation in the grid varies instant by instant depending on the present level of power production and on the surrounding load conditions. It takes into account the reduction of energy production costs (savings in fuel consumption, O&M etc.), the transportation costs and, in some cases, the risk reduction as regards the possible situations of scarcity in given periods (peak hours).

The power distribution grids in LV are often built as radial structures because it is assumed that the level of reliability of components reached nowadays does not justify the use of a net shaped grid. These last in fact, offer a modest improvement of the service but have costs of building, operation and maintenance too high.

The appraisal of the impact of grid-connected PV plants on a LV grid has been performed by a comparison of the photovoltaic production power and local consumption.

Basically, the impact of distributed PV generation depends strongly by the type of loads considered.
If loads are represented by a bank or a supermarket, a certain penetration of PV contribute always to flatten the load curve and, under certain assumptions, to reduce Joule losses along the LV line.
On the other hand, yearly data do not show great advantages in terms of PV capacity, which also in case of high penetration does not exceed a few percent of the maximum load.

1. Introduction

1.1 General considerations

Basically, the *Power Value* may be defined as the economic value of the power produced, given the plant location and its trend of production. This is because the power value is affected by the distance between the power station and the load (decentralised production near the loads is typical for PV) and by the match/mismatch conditions of the production with the trends of the loads in LV branches.
The power value varies instant by instant depending on the present level of power production and surrounding load conditions.

The power value of PV generation in the grid takes into account the reduction of energy production costs (savings in fuel consumption, O&M etc.), the transportation costs and, in some cases, the risk reduction as regards the possible situations of scarcity in given periods (peak hours).
It is well known that this result varies instant by instant. However, the power value of PV generation may be increased by the following distributed benefits:

1. Reduction of Joule losses;
2. Improvement in quality of service in peak hours (voltage stability);
3. Improvement in continuity of service in peak hours (less probability for a LV system to exceed the power limit of a MV/LV cabin, e.g. to avoid the switch-off of the over-current protection device).

Further than these advantages, if we consider a long-term period, the impact of PV affects also the investment for equipment as the followings:

4. Deferral and/or reduction of investment to upgrade the power distribution network (especially the LV distribution grid);
5. Reduction of additional generation capacity;

Last but not least, power production costs from conventional energy sources should include environmental costs as, for instance, pollution and greenhouse effect from thermal power plants, risks for inhabitants from nuclear power plants when present (and also from large hydro) and visual impact from practically every large power station (including wind).
Again, transportation of power needs a network of lines, which have a high visual impact and nowadays are not well accepted by population because they are considered sources of dangerous Electro-magnetic fields.
Considering that power production from PV does not imply consequences of this type, it is possible to refer to this advantage with the following statement:

6. Reduction of environmental impacts.

1.2 Methodology

Power value
In accordance with the given definitions, a calculation or an esteem (if all necessary data are not completely available) of the power value for the PV must consider the following items:

Power value	= Market price of electricity	
	+ Savings in reduction of joule losses	(1)
	+ Improvement of the quality of service	(2)
	+ Improvement of the continuity of service	(3)

+ Savings of investment for additional distribution equipment (4)
+ Savings of investment for additional power production (5)
+ Reduction of environmental impacts (6)

It is possible to note that the power value related to the topics from 1 to 5 strongly depends from the possibility to modify the LV consumption curve in order to flatten it.
Usually, this effect takes place when the trends of loads and PV production are quite in phase and there are not consumption's peaks in the evening or night.

Market price of electricity
The market price might be represented by the sale price if this last reflects the real value of the power delivered instant by instant.
Unfortunately, in many cases the power value is biased by political or commercial influences and so the sale price can be hardly used in calculations.
The recent introduction in many countries of energy meters, which support a multi-tariff system, also for small LV users, leads to a more precise idea of the market price of power.

Savings in reduction of joule losses
The topic 1 (Joule losses) is mainly related with the effects of the decentralised production of electricity. If generators are not far from consumers and PV production is enough in phase with the trend of loads, or at least PV production does not exceed the consumption of the specific branch of grid, savings for reduced Joule effect are considerable.
Calculations may be not easy and shall take into account the type of LV grid, the disposition of loads and PV generators along lines, their power and connection (single-phase or three phase).
If all the PV energy produced is consumed in the specific LV branch, it is possible to calculate joule savings by remodelling the load curve of each self-producer by means of a mere subtraction of the curve of PV production. Negative consumption, i.e. production's excesses, provided they are not too high, may be considered as negligible if it may be assumed that they are consumed in the nearness.
Another positive effect is related to the lifetime of electric lines, especially if these are placed underground. The lifetime of isolated cables shows a strong dependence from their temperature, which is highly dependent from Joule effects. Therefore, a reduction of Joule losses along a line implies less maintenance and longer periods between replacements.

Improvement of the quality of service
The quality of service is, in this case, represented by the possibility to have a more stable voltage because the PV production flatten the load curve and thus reduces the variations of the current along a LV line.
Obviously, this advantage is evident if PV production is enough in phase with consumption in the LV line. If, on the contrary, the two curves are out of phase, the introduction of a PV generator will cause a worsening of the quality of service.

Improvement of the continuity of service
The continuity of service will increase, as much as PV generation is able to make a shaving of consumption's peaks.
This effect may be seen as a lower probability in the occurrence of local blackout.

Savings in investments for additional distribution equipment
This topic is quite similar with the improvement of the continuity of service. A flattening of consumption's peaks may allow avoiding or postponing the reinforcement of a LV grid.

Savings in investments for additional power production
On a larger scale this topic is quite similar with the improvement of the continuity of service and the savings in investments for additional distribution equipment. A generalise flattening of the

aggregate consumption’s curve may allow to avoid or postpone the construction of new power plants.

Reduction of environmental impacts
This calculation may be performed on a small scale in case of small grids or, more frequently, on a larger scale (country level) by considering the average environmental cost of the power production for the specific region or country.
On a global scale it is also important to consider the less introduction of greenhouse gas in atmosphere obtained by means of the use of PV energy.

2. Characterisation of LV grids

2.1 Information on LV grids in Italy

MV/LV Cabin

Generally, MV/LV cabins in Italy have a power capacity up to 630 kVA per transformer and if they use of a pole transformer cannot exceed the power of 100 kVA.

Types of grid

The power distribution grids in LV are built as radial structures because it is assumed that the level of reliability of components reached nowadays does not justify the use of a net shaped grid. These last in fact, offer a modest improvement of the service but have costs of building, operation and maintenance too high.

Radial grids instead, are nowadays the most used and may be realised by using the following configurations of the lines:

- ✓ with joints between cabins, this has the maximum index of re-supplying and must be adopted in build-up areas with cable wiring;
- ✓ with backbones and transversal lines (tree lines), for the users there is not the possibility to be re-supplied for emergency; typically, this solution is used outside of urban centres;
- ✓ With a ring (or petal) normally open, the grid is supplied by one cabin, the back-bone comes out, describes a ring and come back; a switch in a proper point of the line allows the re-utilisation of a number of sub-lines after a damage.

Grid planning

The aims of a LV grid planning are mainly the followings:

- ✓ to maintain into acceptable limits the voltage drops;
- ✓ to obtain the maximum service continuity in the area in consideration of its characteristics;
- ✓ to guarantee a ready answer to the needs of new supplying or increasing of power;
- ✓ to build simple and cheap plants.

From a report performed by Enel it is possible to identify the fields of employment of the various grid structures as a function of the power density. These results are shown in the following tables:

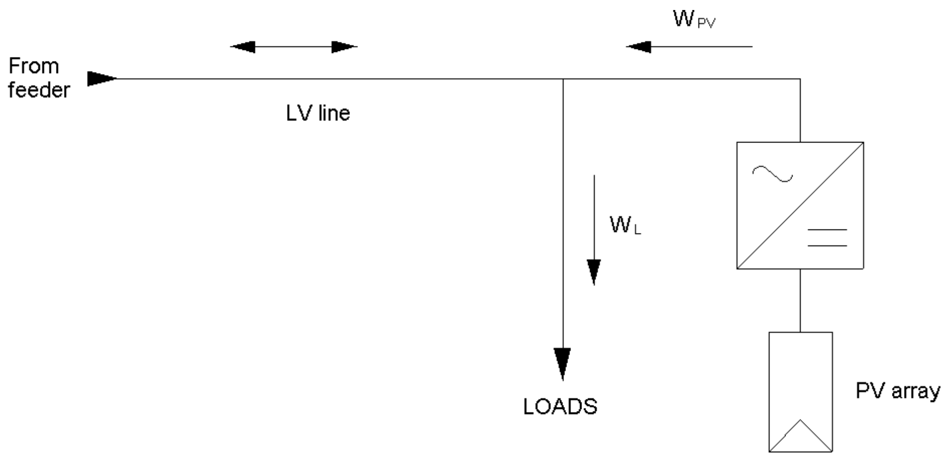
OVERHEAD LINES				
Load distribution	**Type of structure**	**Type of line**	**Outputs per cabin**	**Recommended load density**
Superficial	Tree	Back-bone 70 mm^2 (Al)	4	< 3000 kW/km^2
		Derivation 35 mm^2 (Al)	8	3000 to 6000 kW/km^2
	Joints between cabins	Back-bone 70 mm^2 (Al)	4	6000 to 15000 kW/km^2
			8	> 15000 kW/km^2
Linear	Joints between cabins	Back-bone 70 mm^2 (Al)	2	80 to 200 kW/km^2
			4	> 200 kW/km^2
		Back-bone 70 mm^2 (Al)	2	< 80 kW/km^2
			4	80 to 200 kW/km^2

UNDERGROUND LINES				
Load distribution	**Type of structure**	**Type of line**	**Outputs per cabin**	**Recommended load density**
Superficial	Tree	Back-bone 95 mm^2 (Cu)	4	< 5000 kW/km^2
		Derivation 50 mm^2 (Cu)	8	5000 to 10000 kW/km^2
	Joints between cabins	Back-bone 95 mm^2 (Cu)	4	10000 to 40000 kW/km^2
			8	> 40000 kW/km^2
Linear	Joints between cabins	Back-bone 95 mm^2 (Cu)	2	100 to 500 kW/km^2
			4	> 500 kW/km^2
		Back-bone 50 mm^2 (Al)	2	< 100 kW/km^2
			4	100 to 500 kW/km^2

3. Data comparison

3.1 Basic criteria

The appraisal of the impact of grid-connected PV plants on a LV grid has been performed by a comparison of the photovoltaic production power and local consumption.
In all calculations, percent values have been used instead of absolute values, in order to make comparisons more understandable. In accordance with these criteria, the maximum power production in a year from photovoltaic is represented as a fraction of the maximum load demand, e.g. 50% or 100%.
The following draw shows the model adopted for calculations.



3.2 Loads

The load trends on LV grids are quite variable depending on the type of users, especially those that are mostly served.
Obviously, load trends in an area covered by small industries are different from those measured in a residential one.
Unfortunately, there are not much data available on trends of LV consumption because at this level calculations are usually performed taking into account the maximum allowable powers and daily energies rather than powers.
In this study, three different types of loads located in Rome have been taken into account:

- ✓ Bank
- ✓ Supermarket
- ✓ Consumption of a residential quarter in a town taken from load measurements in a MV/LV cabin

All data have been recorded with a sampling rate of 15 minutes.

3.3 PV production

In grid-connected schemes, production curves of PV plants, as well their power, depend from many factors, further than the peak power of PV generators and the efficiency of other components (inverter).
These may be listed as follows:

- ✓ Tilt and azimuth of the PV generator;

- ✓ Buildings, mountains, trees etc. which may cause shadowing;
- ✓ Alignment of PV arrays that may cause reciprocal shadowing.

Furthermore, the string configuration may play a role by increasing or decreasing the effect of shadows.
Variations in the above mentioned parameters may cause a number of effects in the energy distribution as it is explained here below.

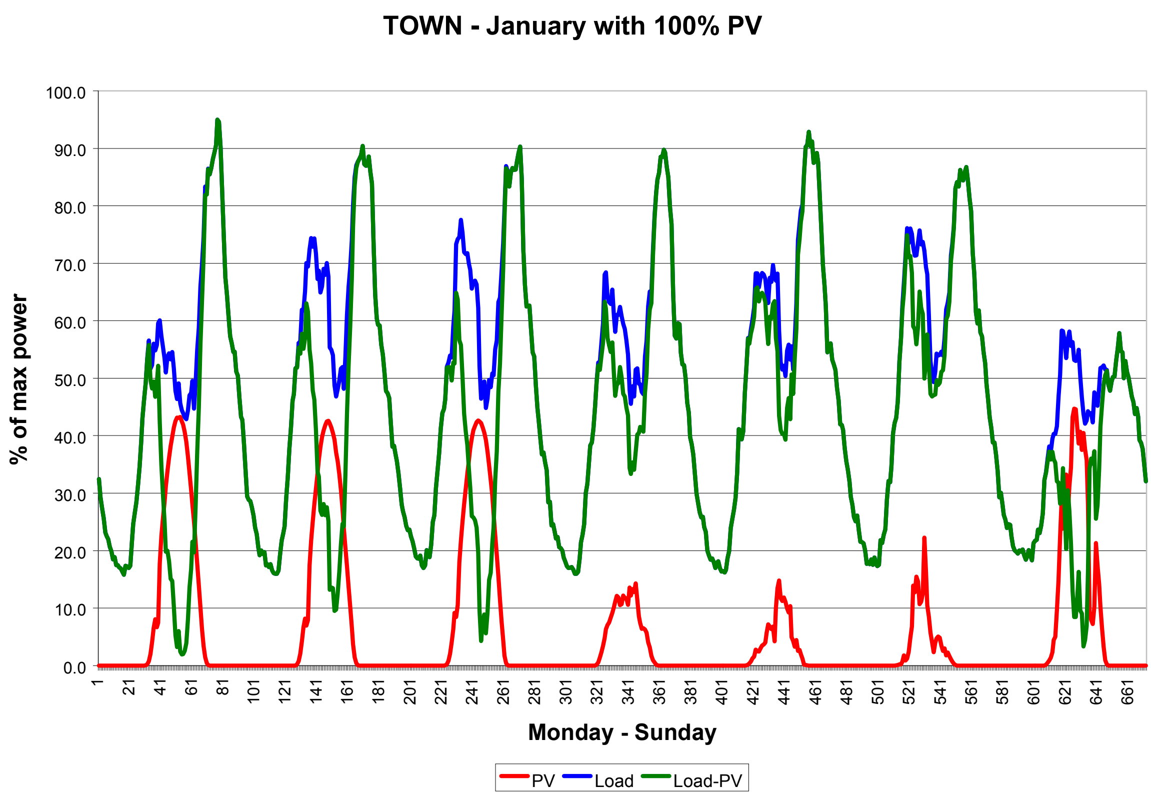
Tilt
Higher values of tilt angle usually increase the power production in winter and decrease it in summer.
Furthermore, when the sun cover a large path (summer period) a high tilt angle restricts the production curve. When tilt is equal to 90° the maximum theoretical visibility of the sun path is limited to 180°.

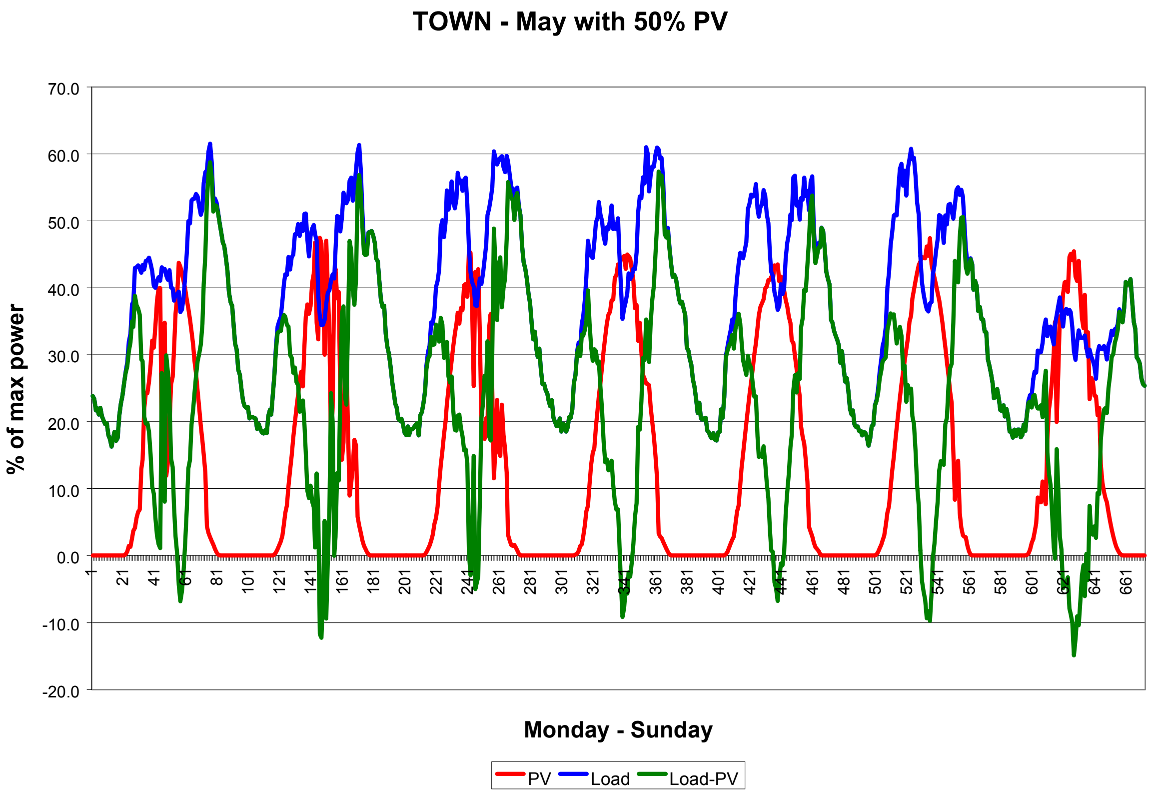
Azimuth
An azimuth different from 180° (south) shifts the theoretical power peak toward east or west according with the orientation of the PV generator.

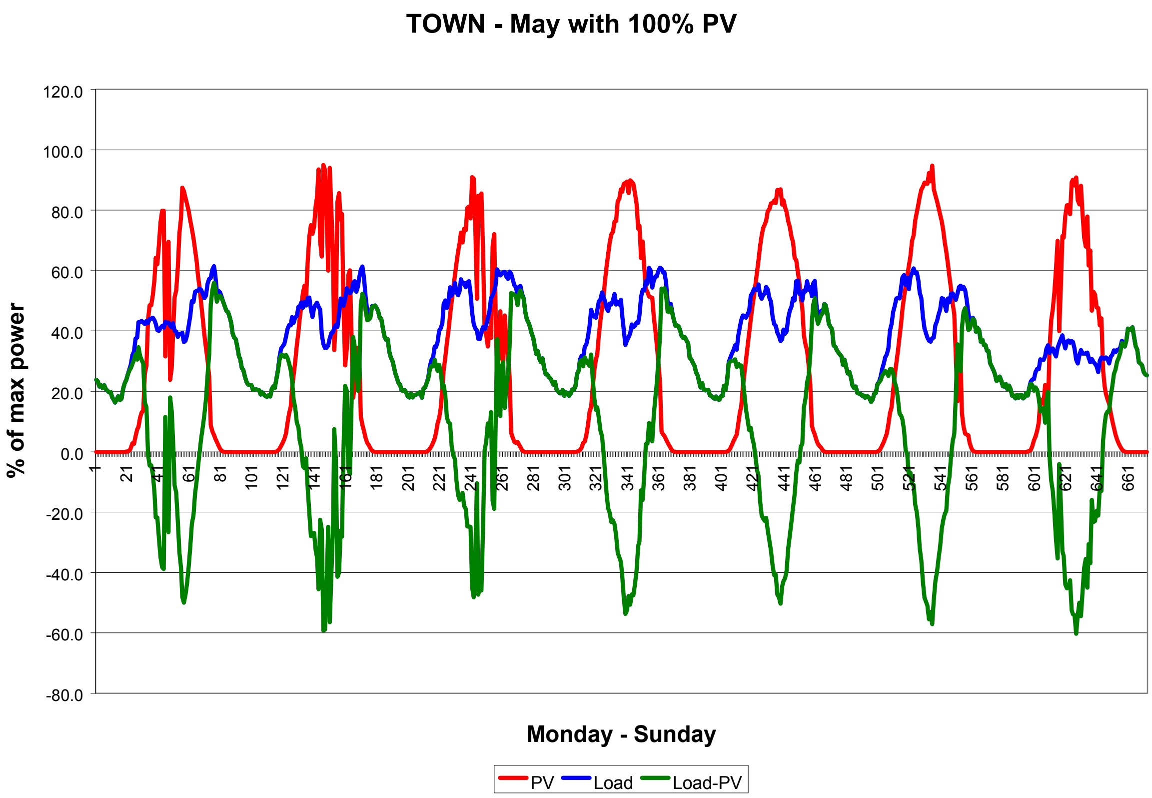
Buildings, mountains, trees etc., reciprocal shadowing
These obstacles may interfere with the visibility of the sun path in particular areas. Usually these effects are particular strong in winter.

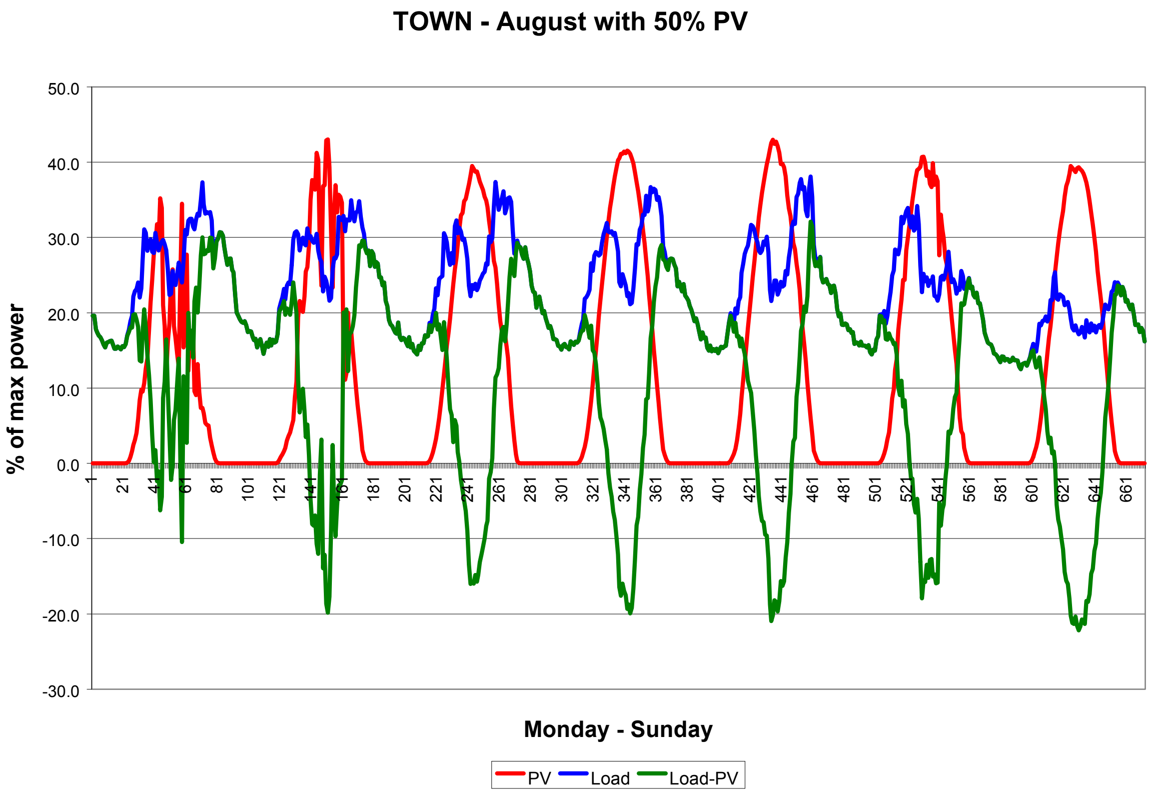
3.4 Consumption of a residential quarter in a town and PV production

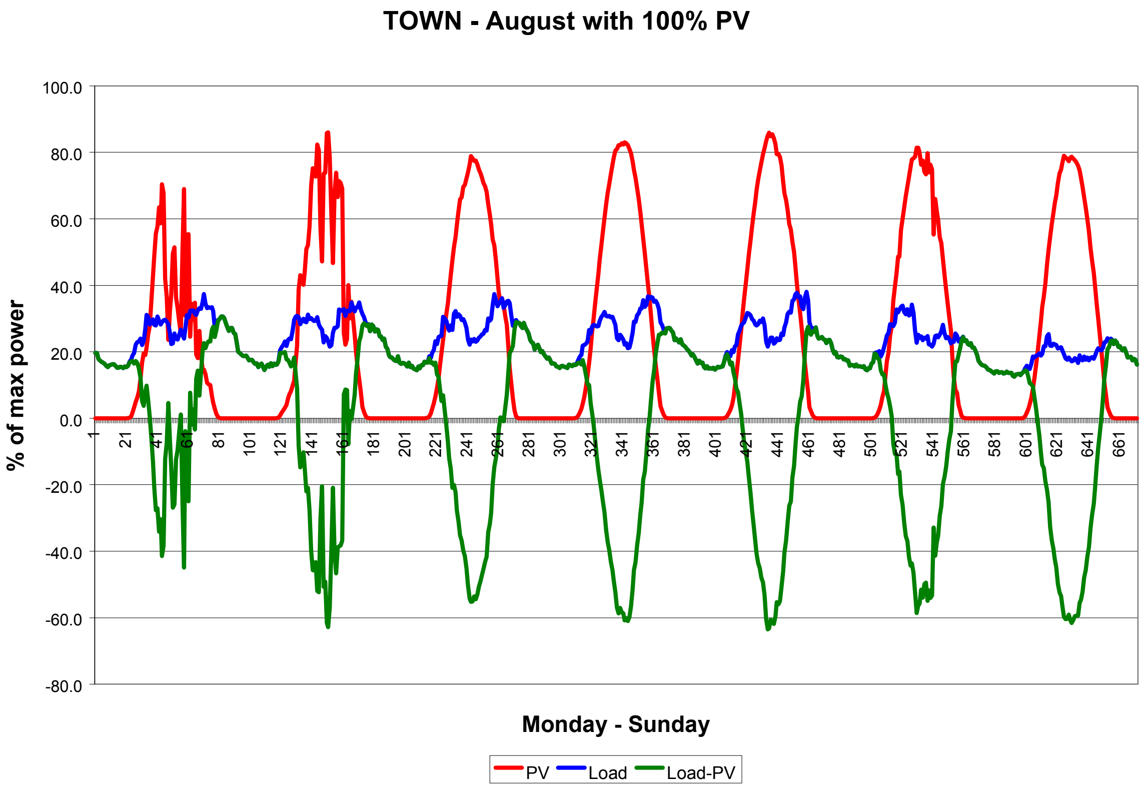
The following graphs show the result of a decentralised power production from PV when loads are represented by a typical urban situation (residential quarter). Each graph represents the trend of a week in the specified month.




TOWN - May with 50% PV
% of max power
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
Monday - Sunday
PV
Load
Load-PV

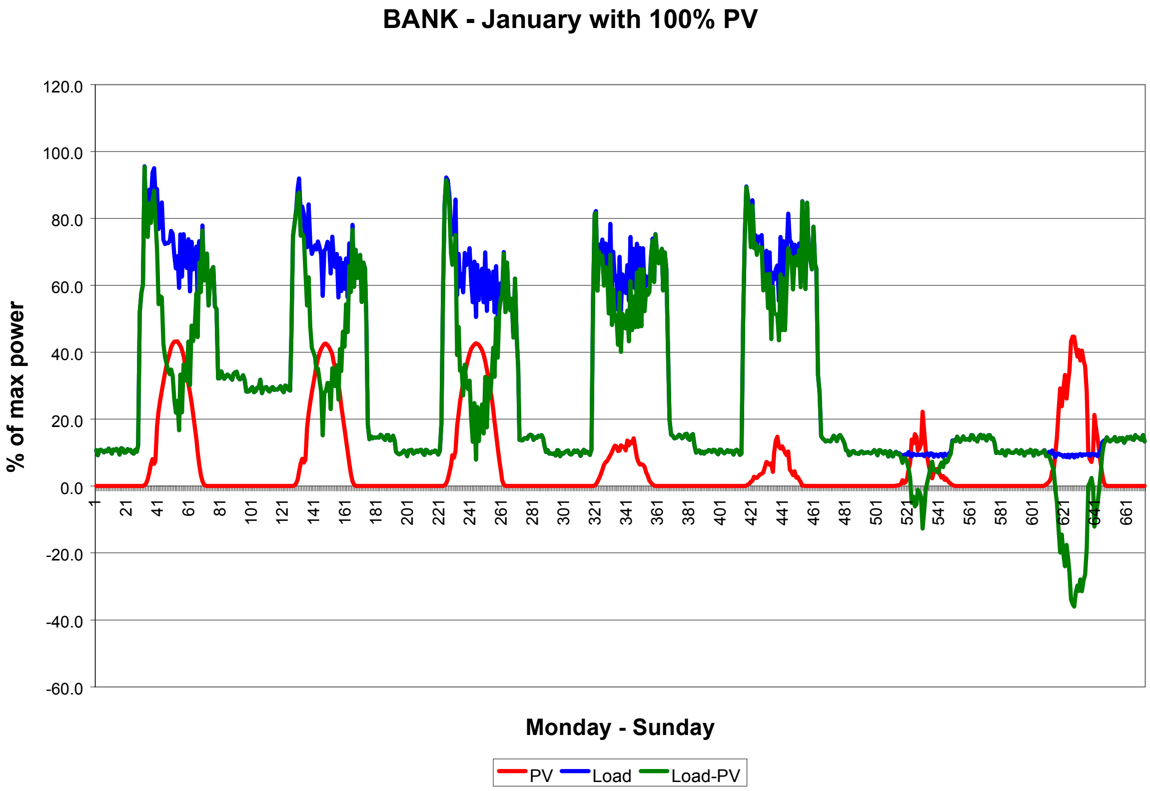

TOWN - May with 100% PV
% of max power
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
Monday - Sunday
PV
Load
Load-PV

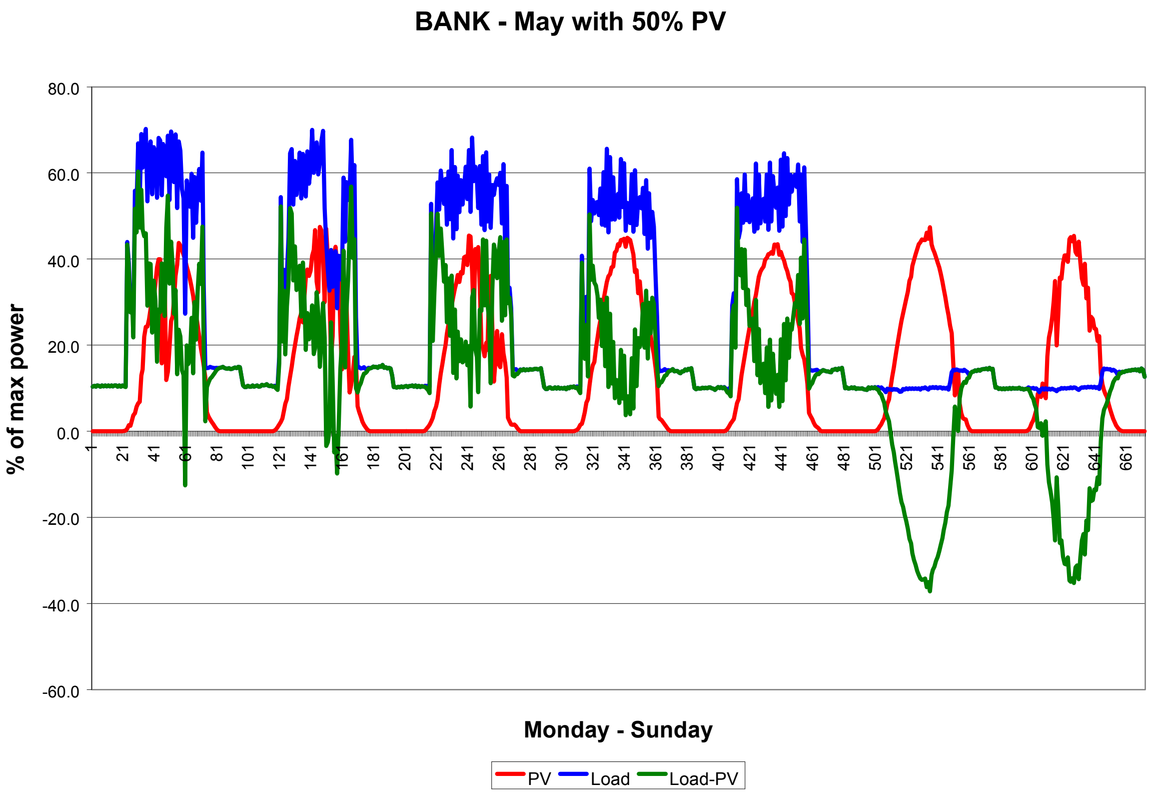

TOWN - August with 50% PV
% of max power
Monday - Sunday
PV
Load
Load-PV

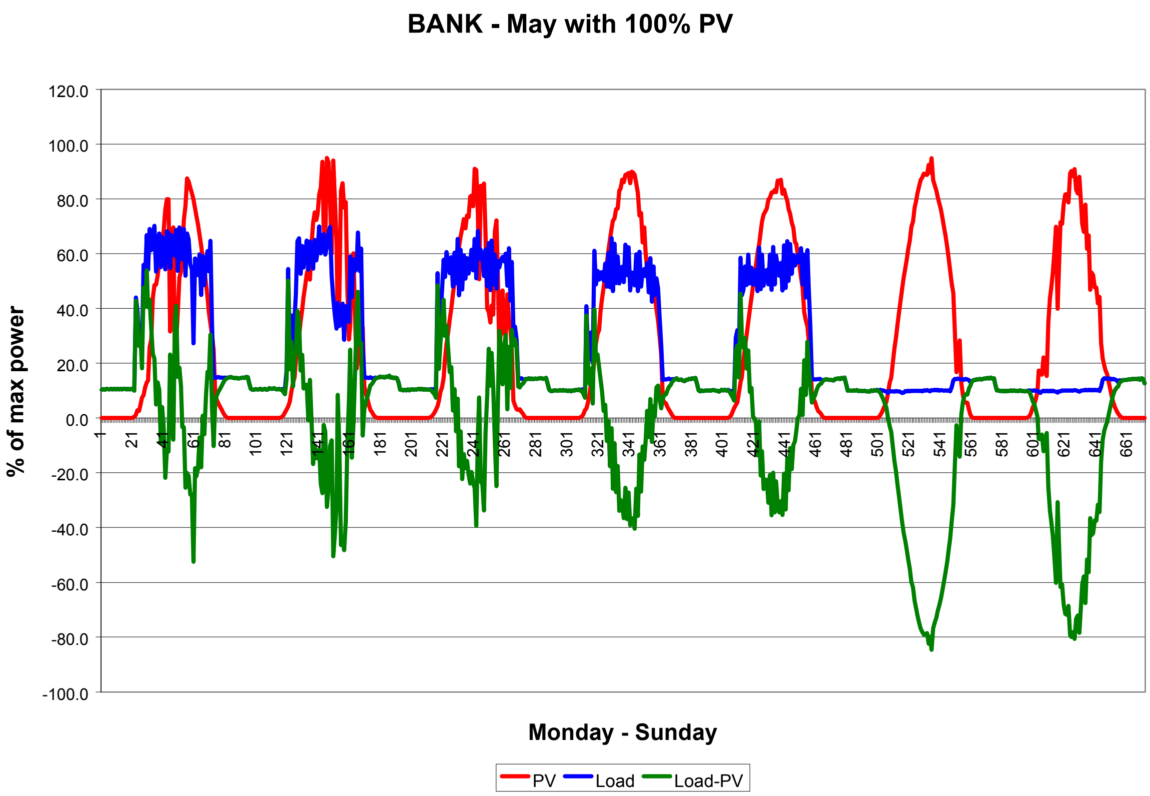

TOWN - August with 100% PV
% of max power
Monday - Sunday
PV
Load
Load-PV

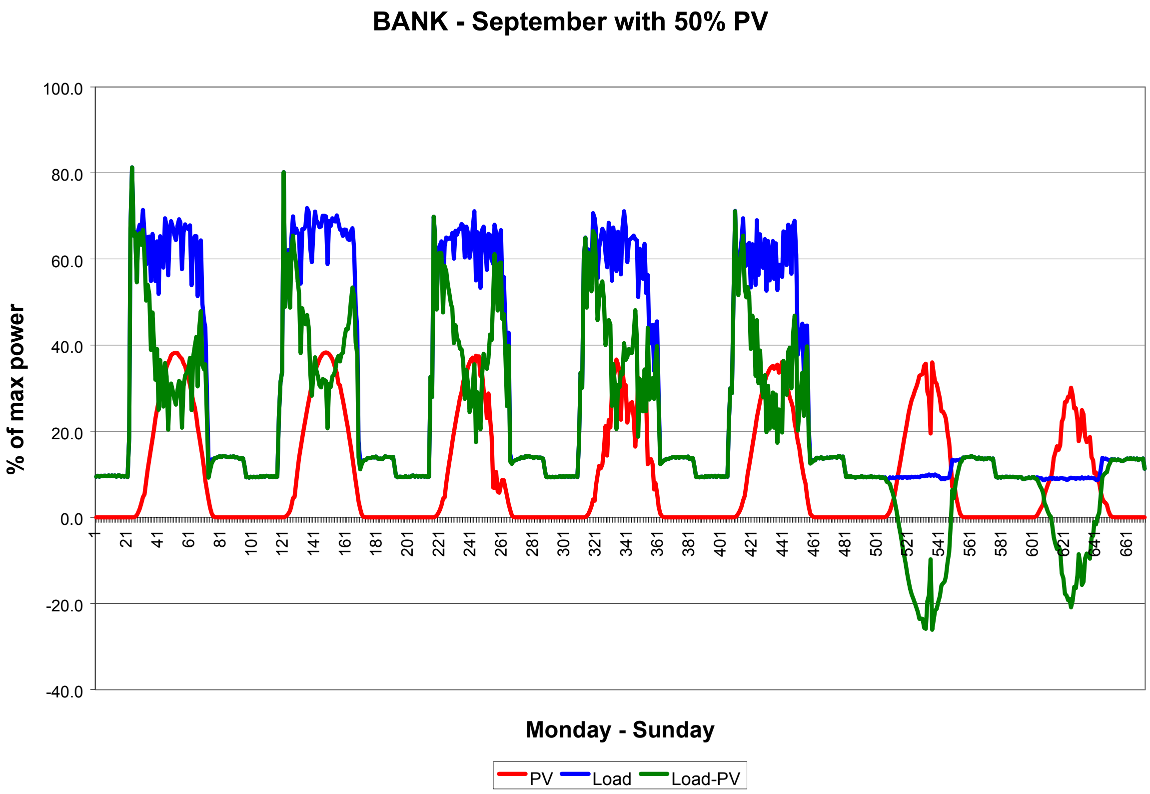
3.5 Consumption of a bank and PV production

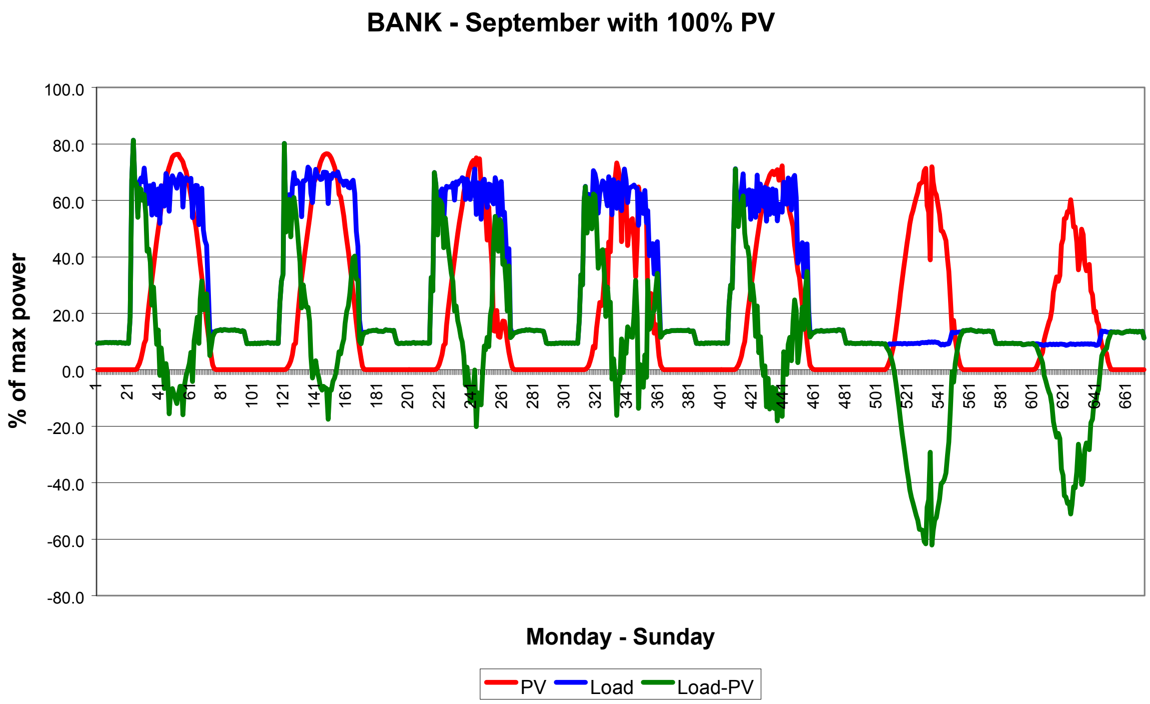
The following graphs show the result of a decentralised power production from PV when loads are represented by consumption of a bank. Each graph represents the trend of a week in the specified month.




BANK - May with 50% PV
% of max power
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
Monday - Sunday
PV
Load
Load-PV

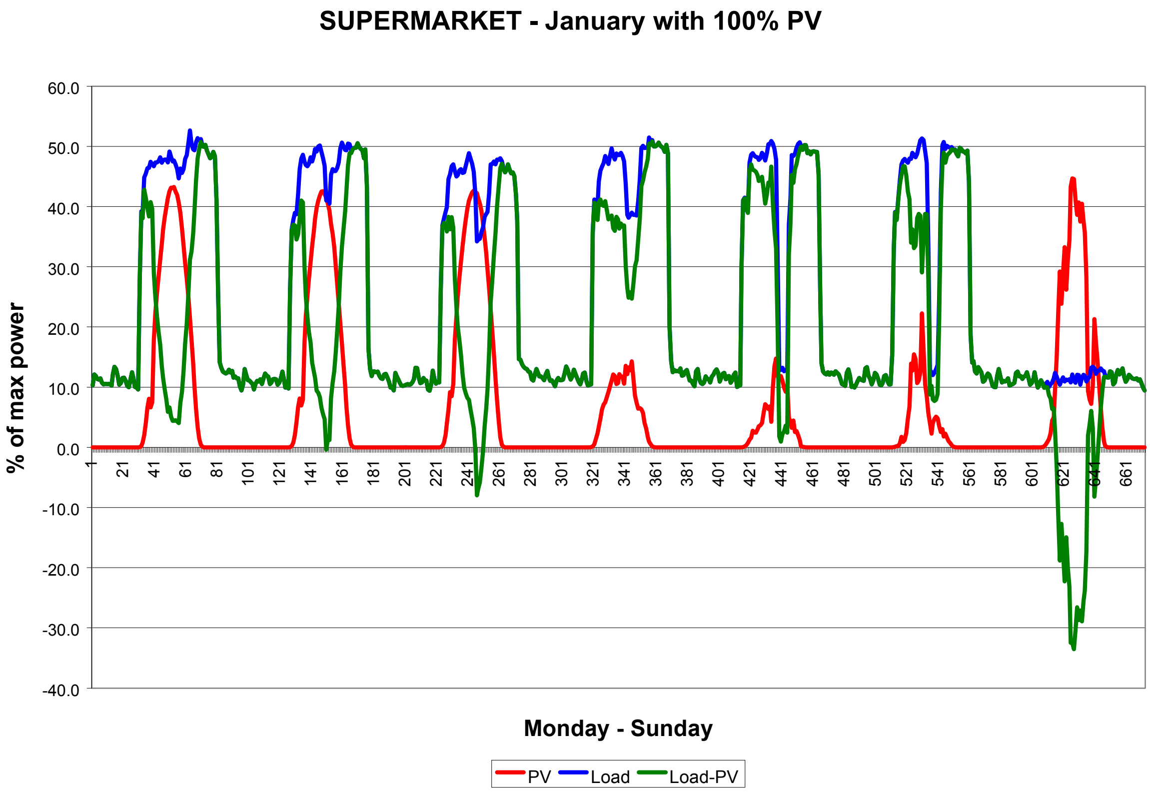

BANK - May with 100% PV
% of max power
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
Monday - Sunday
PV
Load
Load-PV

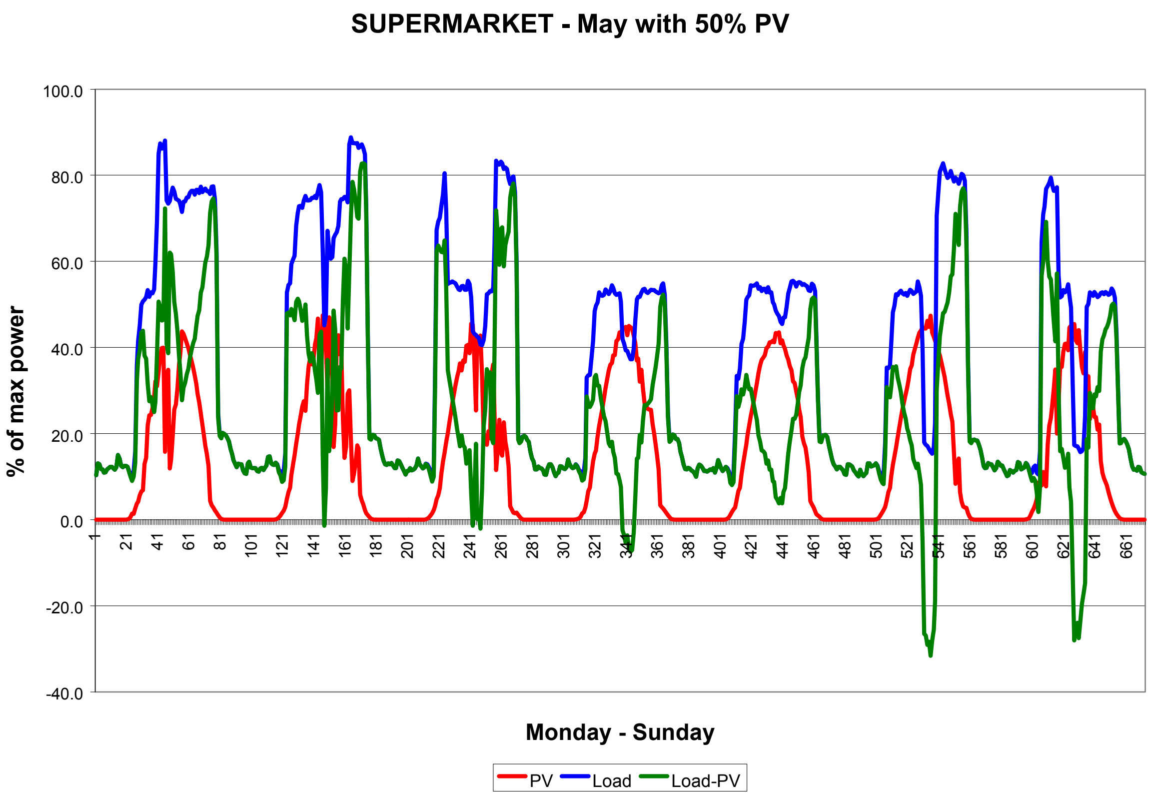


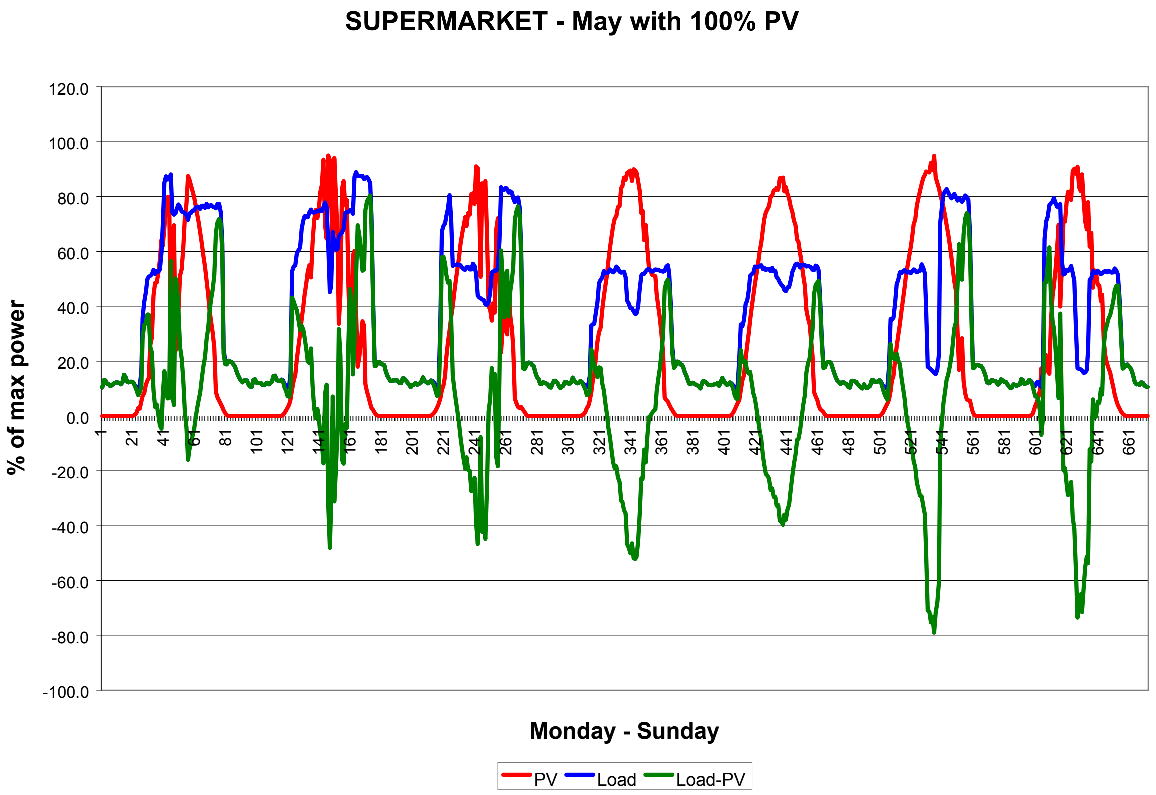


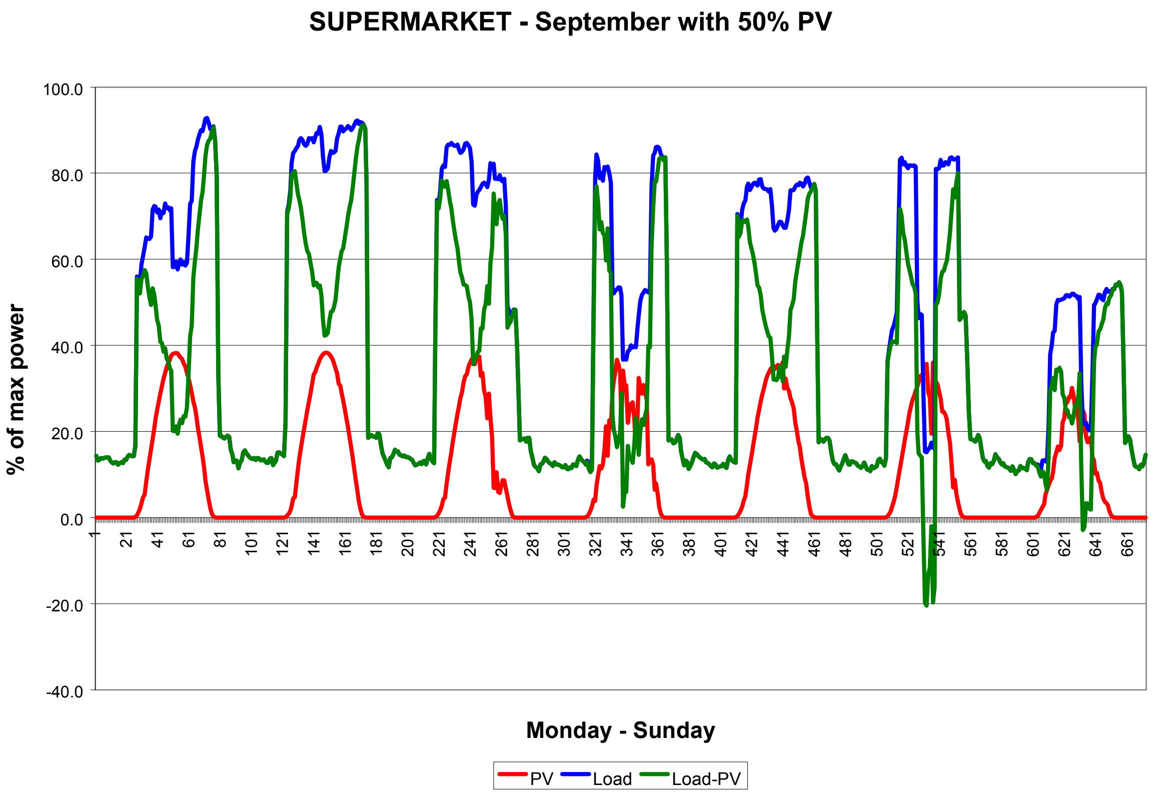
3.6 Consumption of a supermarket and PV production

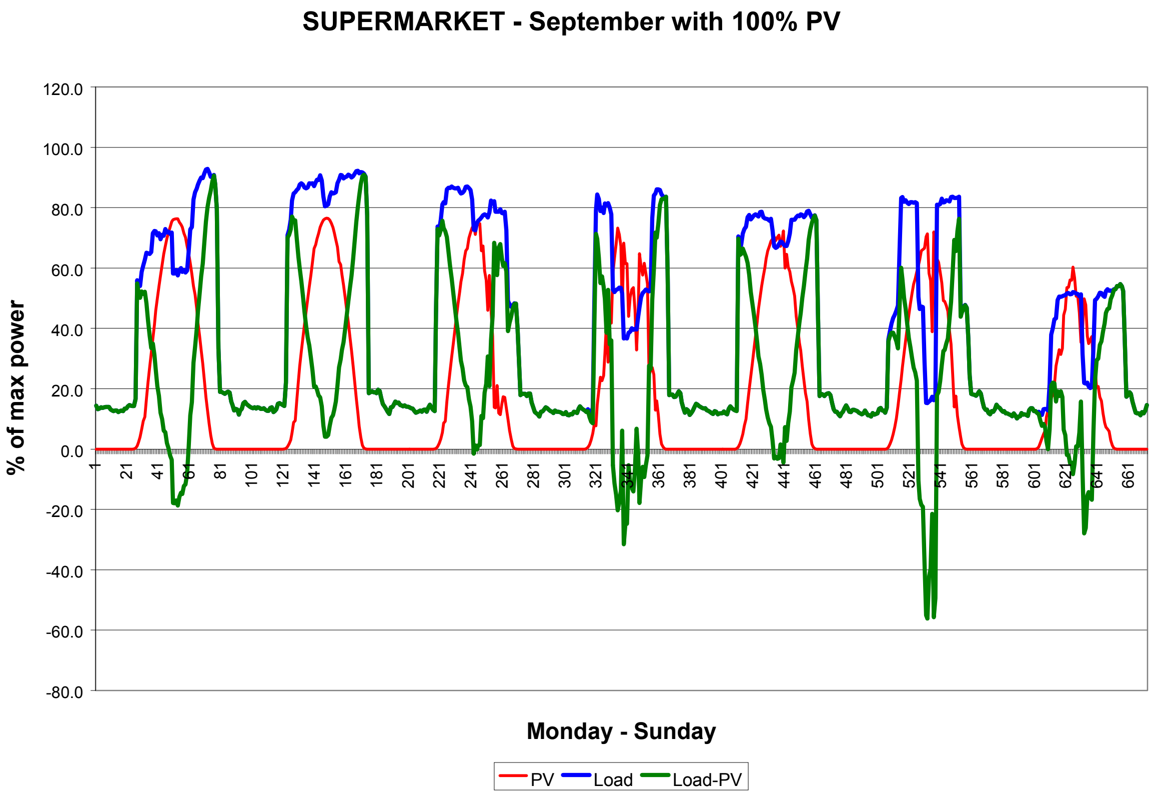
The following graphs show the result of a decentralised power production from PV when loads are represented by consumption of a supermarket. Each graph represents the trend of a week in the specified month.


SUPERMARKET - January with 100% PV
% of max power
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
1 21 41 61 81 101 121 141 161 181 201 221 241 261 281 301 321 341 361 381 401 421 441 461 481 501 521 541 561 581 601 621 641 661
Monday - Sunday
PV
Load
Load-PV


SUPERMARKET - May with 50% PV
% of max power
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
1 21 41 61 81 101 121 141 161 181 201 221 241 261 281 301 321 341 361 381 401 421 441 461 481 501 521 541 561 581 601 621 641 661
Monday - Sunday
PV
Load
Load-PV


SUPERMARKET - May with 100% PV
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
% of max power
1 21 41 61 81 101 121 141 161 181 201 221 241 261 281 301 321 341 361 381 401 421 441 461 481 501 521 541 561 581 601 621 641 661
Monday - Sunday
PV
Load
Load-PV

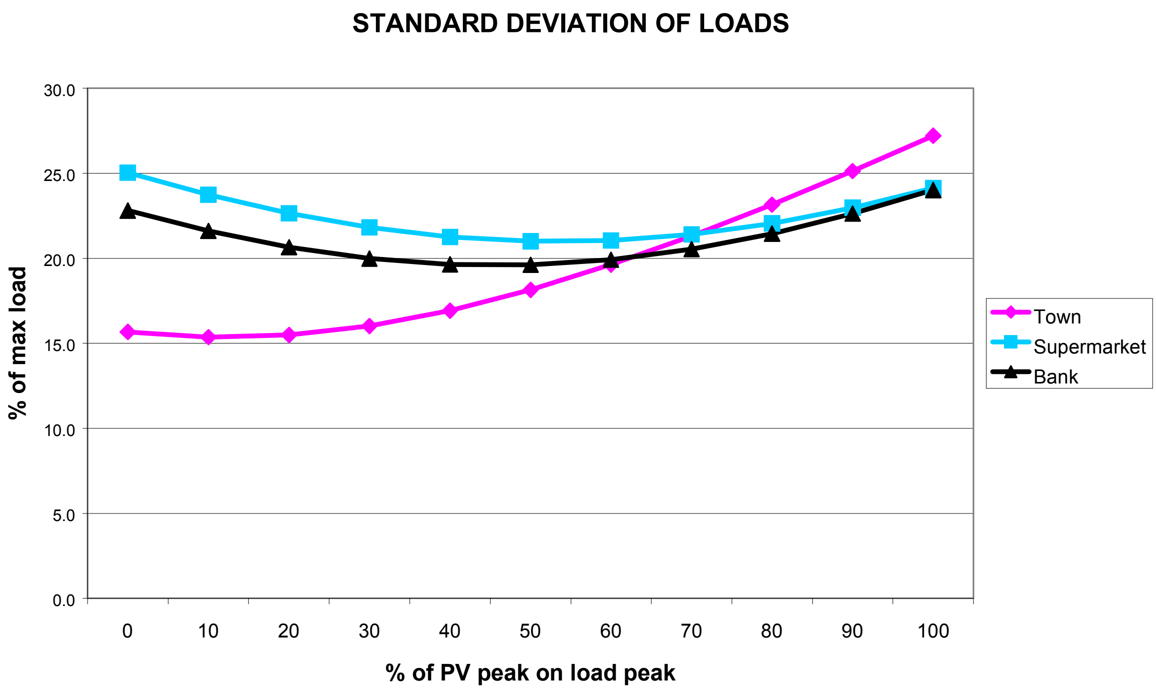

SUPERMARKET - September with 50% PV
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
% of max power
1 21 41 61 81 101 121 141 161 181 201 221 241 261 281 301 321 341 361 381 401 421 441 461 481 501 521 541 561 581 601 621 641 661
Monday - Sunday
PV
Load
Load-PV


SUPERMARKET - September with 100% PV
% of max power
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
1
21
41
61
81
101
121
141
161
181
201
221
241
261
281
301
321
341
361
381
401
421
441
461
481
501
521
541
561
581
601
621
641
661
Monday - Sunday
PV
Load
Load-PV

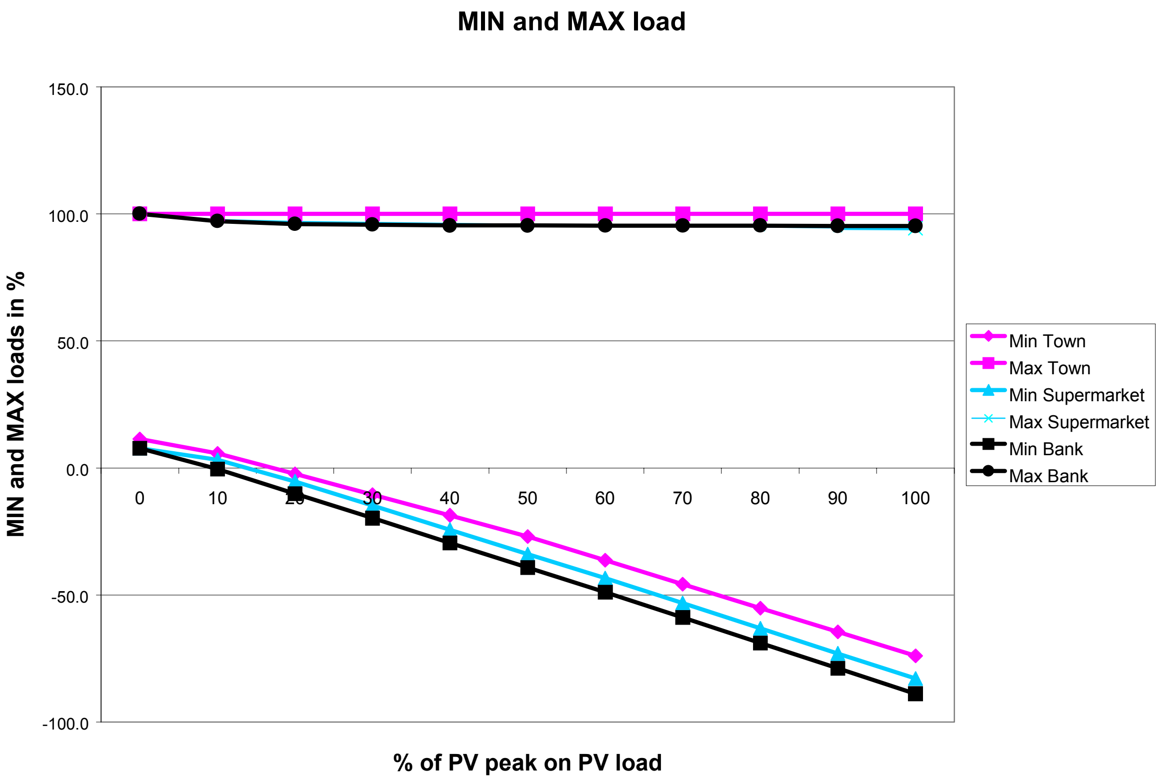
4. Statistics

4.1 Curve flattening and peak shaving

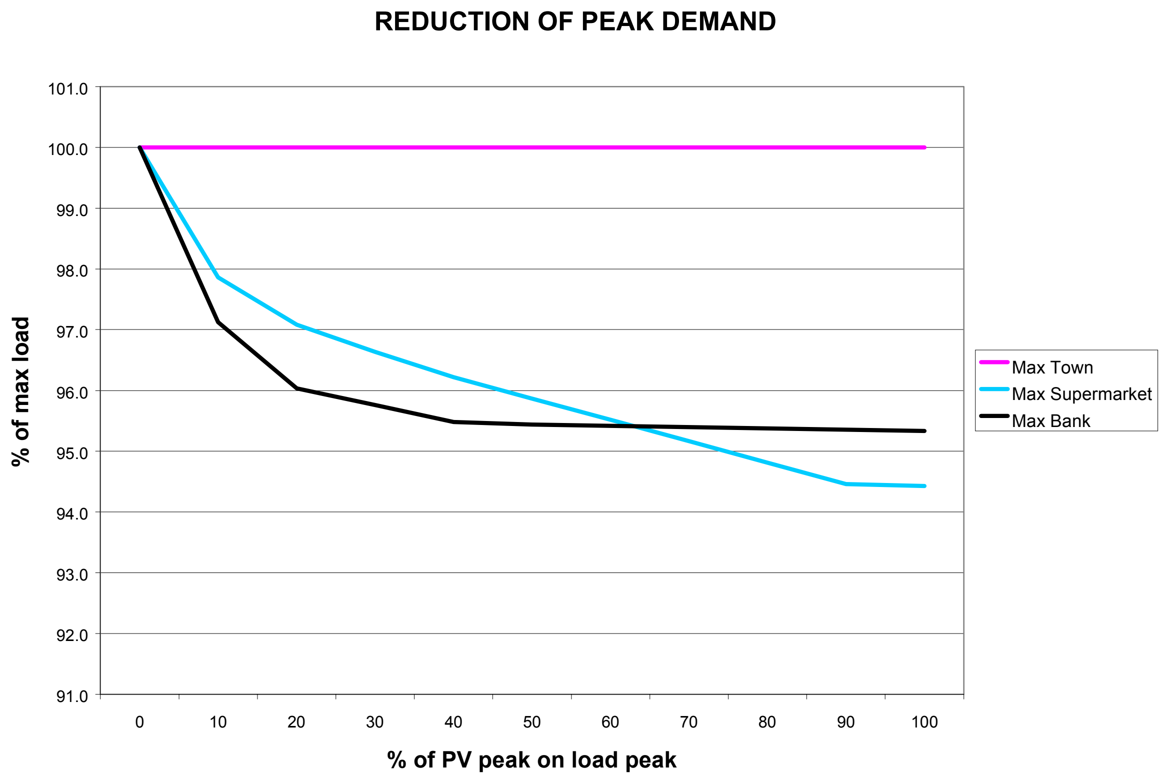
The trends showed in the previous paragraph have been processed on a yearly basis in order to obtain a statistic analysis, which may help to better understand the possible benefits of the distributed production from PV.
It has been told that PV may flatten the load curve and so the first graph refers to the standard deviation of the resulting loads (loads – PV).



From the graph of the standard deviation it is possible to see that a flattening actually occurs if the bank and the supermarket are considered. In these cases, if the PV maximum power is at a level of about 50% of the maximum demand, the maximum effect is obtained.
For the town, on the contrary, a maximum of 10% of PV hardly flattens the load curve, which begins to rise for larger values.
The next graph shows the maximum power ranges depending upon PV penetration.



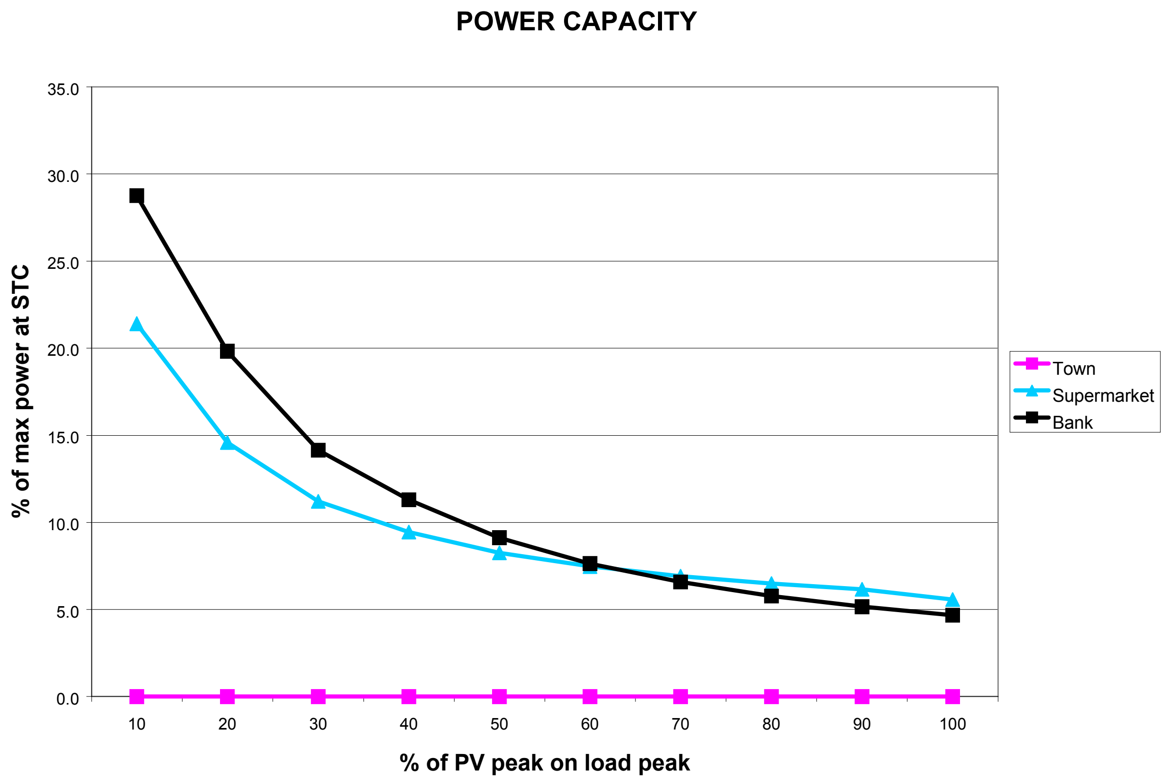
It is quite evident that the introduction of PV increase the power range: with a penetration from 10% to 17%, practically all types of loads reach the point of zero-consumption; for higher PV penetrations the maximum values of the power exported increase almost linearly.
On the front of the reduction of peak demand, results are not so enthusiastic, because shaving is always not more than a few percent. In order to have a better view of this behaviour, the next figure shows an expansion of scale for the previous graph.



The graph, which shows the reduction of peak demand, gives also a clear idea of the power capacity of PV in the three different situations.

If compared with the power output of a MV/LV cabin, PV does not increase the power capacity of the system at all. On the contrary, in case of a bank the power capacity increases rapidly with the PV penetration but this effect becomes exhausted after about a 30% of PV. If we consider a supermarket, the power capacity of PV shows saturation for a penetration larger than 90%.

The calculation of the power capacity of PV as a percentage of the rated power in different situations is well expressed by the following graph.



In the most favourable case (bank and 10% of PV penetration) the power capacity of PV is almost a 30% of its rated power, but this ratio drops dramatically as the presence of PV becomes higher.

4.2 Reduction of Joule losses

If we assume that voltage drops along the line is not too high, it is possible to adopt a simplified model for the calculation of the power losses[1].

$$W_S = f\,(W_L - W_{PV})^2 \,/\, W_{LMAX}$$

Where:
W_S is the power lost along the line
W_L is the consumption
W_{PV} is the power produced by the PV plant
W_{LMAX} is the maximum value of consumption in the year
f is the maximum voltage excursion along the line (it has been adopted a 10%, that is a variation of ±5%)

The following graph shows the results of the application of this model to the input data.

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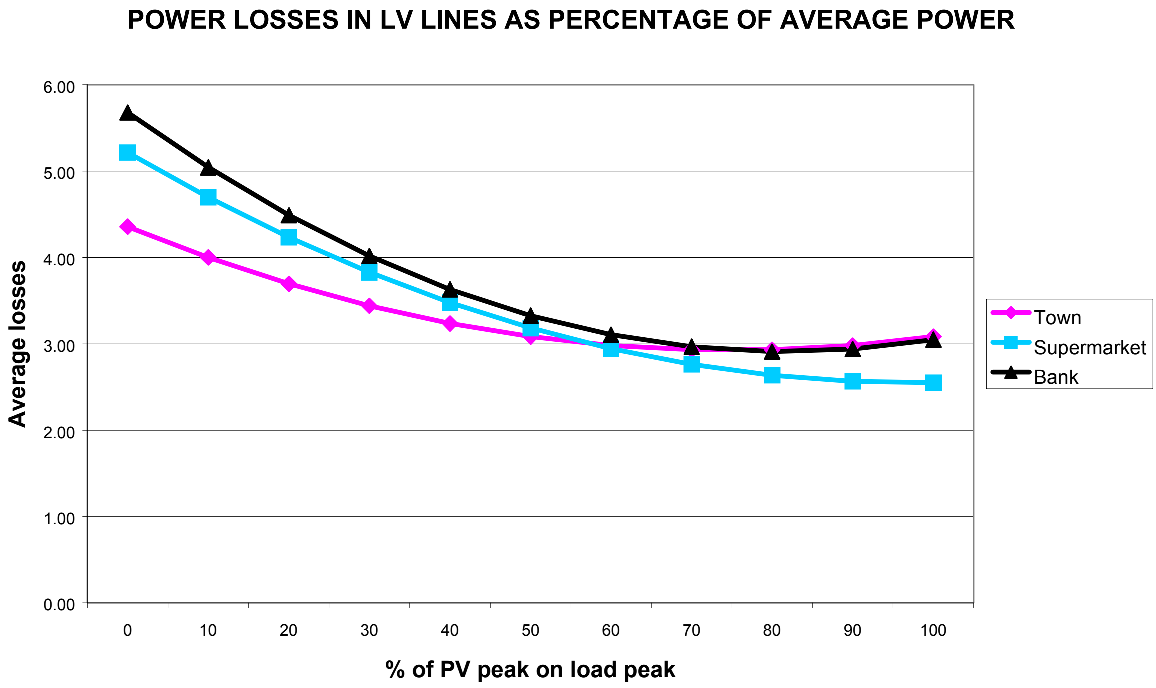
[1] If Z_S is the impedance of the line and Z_{LMIN} is the equivalent impedance of loads at rated power, it may be assumed that Z_{LMIN}™Z_S. Thus the maximum voltage variation at the end of the line is $\Delta V_{MAX} \approx Z_S/Z_{LMIN}\ V_F$, where V_F is the output voltage of the feeder. On the other hand, the value of ΔV_{MAX} cannot exceed a fraction of V_F, that is $\Delta V_{MAX} = f\ V_F$, and so $Z_S = f\ Z_{LMIN}$.
By the introduction of PV, the current along the line is equal to the current though loads less the current supplied by the PV system, thus $W_L = Z_L\ I_L^2$ and $W_S = Z_S\ (I_L\text{-}I_{PV})^2$. Thus we obtain:
$W_S/W_L = (Z_S/Z_L)\ (I_L\text{-}I_{FV})^2/I_L^2 = f\ (Z_{LMIN}/Z_L)\ (I_L\text{-}I_{PV})^2/I_L^2$. From last equation, with a few passages it is possible to obtain the formula used in the text.



From this graph it is possible to see that power losses along the line reach a minimum for a high penetration of PV, that is 80% for town and the bank, and even more (90% to 100%) for the supermarket.
The loss reduction due to the introduction of PV may reach almost a 3% for an optimum configuration and if a bank or supermarket represents loads.
If a MV/LV cabin is considered, the reduction is not higher than a 1,5%.
Anyway, a mere 3% of loss reduction on a 6% total means a 50% less of thermal effects on the cable, while a 1,5% of loss reduction may be traduced in a 25% less.
As it was told before, the less a cable is warmed the more its lifetime is high; therefore it may be expected that the presence of PV along LV lines imply their longer duration.

5. Conclusions

Data comparison and analysis from PV production and loads in a LV grid may lead to some interesting conclusions.
Basically, the impact of distributed PV generation depends strongly by the type of loads considered.
If loads are represented by a bank or a supermarket, a certain penetration of PV contribute always to flatten the load curve and, under certain assumptions, to reduce Joule losses along the LV line up to a 3%. In spite of the slightness of this value, the lifetime of lines may increase considerably because of the less thermal stresses.
On the other hand, yearly data do not show great advantages in terms of PV capacity, which also in case of high penetration does not exceed a 5% of the maximum load.
If PV generation is associated with residential consumption, benefits are difficult to single out. In practice, a slight reduction of the standard deviation of the curve is visible only for a penetration not higher than a 10 to 20% of the maximum load. Higher penetration tends to reduce Joule losses but this saving hardly reaches the 1%.