42nd. IAEE International Conference. Local, Energy, Global Markets.
Montréal (Québec, Canada)

A Stylized Economic Model on PV Prosumers Encompassing Generation and Storage Economic Requirements, Load Management, Grid Exchanges and Regulation Rules.[†]

by
Pere Mir-Artigues
Energy Sustainability Research Group, University of Barcelona, Barcelona
&
Pablo del Río
Institute for Public Policies and Goods/CSIC, Madrid

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Pere Mir-Artigues
Energy Sustainability Research Group, University of Barcelona
Applied Economics Department
University of Lleida
Carrer de Jaume II
25001 Lleida
+34-973703212
peremir@econap.udl.cat

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Driven by technical advances and favorable regulatory measures (albeit only in a few countries), the deployment of electricity generation at very small scales, or micro-generation, is shaping a new segment of the electricity system. On-side microgeneration provides electricity services to homes and commercial and industrial businesses from their own premises. Microgeneration can use very different techniques and fuels. Our contribution focuses on photovoltaic (PV) demand-side generation in residential houses, shops, warehouses or industrial buildings. As it is known, these PV plants currently have up to 25 kW. However, there might also be plants with capacities up to 500kW, e.g., shopping malls or industrial warehouses. All these cases can be considered micro-Photovoltaic Generation (mPVG) if the generated electricity is not to be sold only in the market. The mPVG plants increasingly include batteries and, in a not distant future, devices for load management. Load management embraces energy savings and energy efficiency goals which could be achieved through measures such as the installation of appropriate appliances, the improvement of the building insulation, the optimization of lighting points, and so on. As a result, the mPVG plants will become a non-negligible techno-economic complex. The three pillars of mPVG (generation and storage, load management, and grid exchanges) will be on the one hand influenced by specific regulations and, on the other hand, by factors such as income, household composition and lifestyle. Our contribution proposes a stylized model to highlight the main economic and regulatory factors shaping mPVG.

[†]The research leading to these results has received funding from RecerCaixa.

1. General features

Two general features of the mPVG economic regime should be considered: there are no (retroactive) changes in regulation and the plant has been financed with a bank loan, which gives rise to a constant annuity, denoted as a, for depreciation. It is also useful to identify the annual allocation for the specific investment in generation equipment (a_G). Given that those terms refer to the whole year (8,760 hours), the corresponding charges per hour would be denoted as a^h and $a^h{}_G$, respectively. It should be additionally taken into account that a mPVG plant does not have the permanence of real property, since it is a kind of durable goods. Therefore, it is assumed that the depreciation period (T) and the interest rate (i) are those of consumption credits (car purchases, building refurbishments, etc…) rather than mortgages, although there might be support schemes which reduce such rate (not included in the suggested model).

2. Generation, load management and battery performance

To start with, be **q** the vector of the hourly generation **q**=[q_1, q_2, ..., q_t, ..., q_{24}], whose elements are measured in kWh. Their sum is the total daily generation (q). The vector **q** shows positive values for the hours of the day with PV production.[1]

With respect to demand, let **x** be the hourly loads vector, **x**=[x_1, x_2, …, x_{24}], expressed in kWh.[2] The elements x refer to the daily load. Its composition includes the demand from the shiftable and non-shiftable appliances. Regarding the former, their use has been previously programmed by the consumer, whether directly or through the setting up of a mechanism which responds, for example, to prices. It is assumed that there are time-of-use (TOU) rates, which encourage load shifting, and that the prosumer is connected to a smart grid which is able to transmit such information.

The period of time in which both **q** and **x** are defined is τ=[0, 24 hours].

A set of electricity devices deals with load management (L^M).[3] The implementation of those control systems requires a distinction between the following types of consumer loads (Zipperer et al 2013, Longe et al 2017: 4): [4]

- Non-shiftable appliances (or non-schedulable devices) such as lighting, cooking system or TV set.
- Shifttable appliances, which can be divided in,
  - Flexible appliances (or power-shiftable): their operating level can be changed at will, so their amount of power consumption can be shifted in

[1] Vector **q** is a simplification. On the one hand, given that the level of generation changes throughout the seasons (in mid latitudes), a greater realism would require that we have a **Q** matrix with 12 rows (average monthly values) and 24 columns (hours in a day).

[2] As it is known, residential electricity demand changes during the year for climate and social reasons (weekends and holidays). Thus, if the model were defined at an annual scale, then an **X** matrix would be defined with 12 rows (average monthly values) and 24 columns (hours in the day).

[3] Their O&M costs are expected to be very low.

[4] The model does not consider who manages the consumer loads. One possibility is the prosumer himself, although advanced smart grids allow the remote activation of appliances. However, this latter way is viewed with suspicion by many prosumers: it is regarded as an intrusion on privacy (Goulden et al 2014: 21 and 26, Parag 2015: 17).

response to retail price or consumer convenience. This is the case of air-conditioner devices, space heater, etc.

  - Deferrable appliances (or time-shiftable): their energy consumption can be delayed. There are two cases: interruptible loads, such as clothes dryer or garden watering pump (certain tasks are temporally stopped and scheduled to continue later) and uninterruptible loads, such as washing machines and dish washers (they cannot be stopped during operation cycle but their starting time can be postponed at will).

The stylized modeling of load management may be developed by considering that a given home appliance, k, is daily active during a certain time gap, $\tau^k = [t', t''] \leq \tau$, be it the result of a previous programming or not. Therefore, energy demand by a given k electric appliance is given by,

$$x^k = \sum_{t'}^{t''} \sigma_t^k$$

where σ^k is its particular consumption. Then, the daily load is the sum of the electricity consumption on all appliances,

$$x = \sum_k \sum_\tau \sigma_t^k$$

It is assumed that the domestic electricity consumption is never null. This is due to the stand-by mode of some appliances, the presence of refrigerators or the existence of night lights.

The management of shiftable appliances is what makes sense to load management. Those are the only devices which operation can be adjusted at will. These appliances can reduce the economic impact of the electricity consumption by three ways:

- As a result of a fine tuned device operation, it happens $\alpha^k \cdot \sigma^k$, $0<\alpha^k \leq 1$. For example, the thermostat strictly controls the heating system.
- The appliance time of use is curtailed: $\tau^* < \tau$. For example, the air conditioning system works less time than usual.

Therefore, the impact of the load management in reducing the daily cost of electricity consumption is given by the expression:

$$L^M = \sum_k \sum_\tau e_t \alpha_t^k \sigma_t^k + \sum_k \sum_{\tau^*} \sigma_t^k + \sum_k \sum_\tau (e_t - a) \sigma_t^k$$

Load management system decides that the appliances will be fed by the battery during the intervals in which the retail electricity price (e_t) (€/kWh) is $a_G < a < e_t$. The main goal is to reduce electricity imports.

The σ_t^k elements result from the saving and energy efficiency measures implemented in the past, as well as decisions to be taken in the near future. For the sake of simplicity, it is supposed that the equipment purchases and investments in residential premises (insulation, heating system, etc.) are paid cash. As it is known, domestic appliances are considered durable consumption goods and, for this reason, the depreciation calculus are not applied.[5] Moreover, the impact of load management can be polished the more fine tuned is the time resolution.

The aforementioned L^M concept is defined for a given installation. However, seen from a dynamic perspective, load management also includes the gradual substitution of appliances by more efficient ones. As it is well known, investments in more efficient systems may lead to a rebound effect, i.e., the recently bought appliance will lead to a greater use overtime (without affecting the quality of service), which will lead to an energy saving which is lower than the potential one. For example, energy-efficient light bulbs are installed but they are switched on for a longer time, or the thermostat of the heating system is set at a higher level than before.[6] Figure 1 shows the different possibilities.

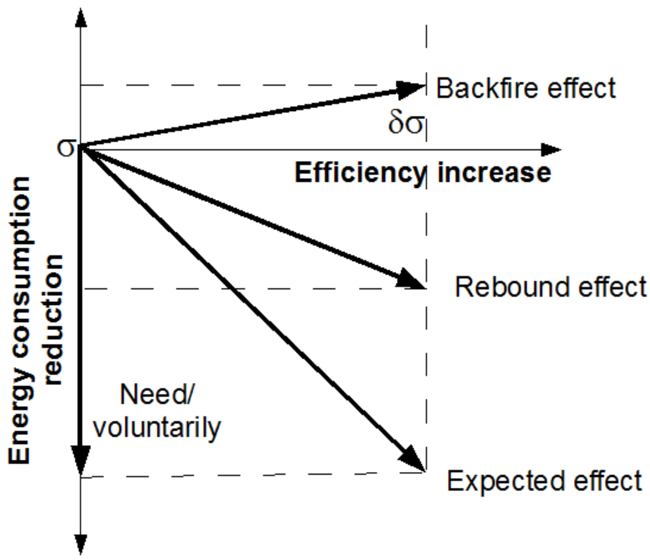


Figure 1. Energy saving and efficiency

The figure has been built based on the assumption that the price of the most efficient appliance is not a barrier to its purchase and that the price of electricity is outside the considered circumstances. In addition, the analysis is only related to the limits of the home, i.e., only direct effects are considered. Then, at the moment when more efficient appliances are installed, the following four situations are possible:

- The point σ indicates a new appliance which does not have a higher efficiency level. However, the consumer decides to reduce its use (and, thus, electricity demand) either due to volunteerism (perhaps due to environmental awareness) or need (absence of economic resources).
- When the efficiency has improved until $\delta\sigma$, $0<\delta<1$, the reduction in energy consumption reduction should be the one indicated by the expected effect.
- The rebound effect results from an increase in the use which partially offsets the potential savings due to efficiency.

[5] The outlays in building refurbishments addressed to energy saving and efficiency improvement (such as walls insulation and heating system upgrading) are not explicitly included. Their economic effects are indirectly considered. These expenditures could be recuperated in renting or selling the building.

[6] Because of the model is defined in daily terms, the weekly or monthly increase in the use of a more efficient washing machine could be integrated by considering a daily average use increase.

- The backfire effect occurs when the use of the most efficient system increases to such extent that it totally offsets the improvement in efficiency.

If an appliance is replaced by a more efficient one, with a consumption of $\delta\sigma$, the final electricity saving s_t^k, is equal to

$$s_t^k = \sum_{\tau} e_t(\sigma_t^k - \delta\sigma_t^k) - \sum_{\tau^*} e_t \delta\sigma_t^k$$

where τ^* is the additional use of the new appliance. Table 1 shows the respective expression for the different cases of figure 1.

Table 1. Efficiency and electricity consumption

Case	Related expression of s_t for the k item
Voluntarily or need	$\alpha^k \cdot \sigma^k$ and/or τ^k reduction
Expected reduction	$\sum_{\tau^*} e_t \delta\sigma_t^k = 0$
Rebound effect	$s_t^k = \sum_{\tau} e_t \sigma_t^k - \delta \sum_{\tau+\tau^*} e_t \sigma_t^k > 0$
Backfire effect	$s_t^k < 0$

Coming back to the model, the performance of the battery involves the following elements (see Böcker et al 2015, Quoilin et al 2016: 61-62, Longe et al 2017):

- Let b_t^+ be the energy charging profile and b_t^- the energy discharging profile both in a given t. As expected b_t^+, b_t^- ≥ 0. Unfortunately, batteries have different losses: let β_t^+ and β_t^- be the charging and discharging efficiencies, respectively, which fulfill conditions $0<\beta_t^+\leq 1$ and $\beta_t^- \geq 1$.[7]
- A maximum charge capacity (b^{max}) and a maximum depth of discharge (b^*) should also be considered.

If b_t^+ is the amount of energy from the PV plant feeding the battery, the energy effectively charged is $\beta_t^+ \cdot b_t^+$. Conversely, if b_t^- is discharged from the battery to the home appliances, then only $\beta_t^- \cdot b_t^-$ is effectively discharged.

The main features of the model developed later make it recommendable to define the hourly charging/discharging matrix as follows:

$$\mathbf{B} = \begin{bmatrix} b_1^+ & \dots & b_{24}^- \\ b_1^- & \dots & b_{24}^- \end{bmatrix}$$

[7] For the sake of simplicity, the battery's energy leakage rate has not been considered. This is a small figure anyway: 0.03% per day (Hoppmann et el 2014: 1106). It should be mentioned that the β gets worse when the battery gets older.

Some of the elements of this matrix are null and assuming, for the sake of simplicity, that both operations do not happen in the same hour. Then, the amount of electricity charged/discharged at time *t*, can be denoted **βB**, with **β**, **β**=[β_t^+, β_t^-] being the efficiency vector.[8] Moreover, **βB**≤b^{max}.

As it is well-known, batteries store DC, which requires a specific inverter or to share the inverter of the PV panels (Luthander et al 2015: 86, MacGill and Watt 2015: 235). The battery receives/feeds electricity from/to the inner grid, although there might also be installations in which the battery may directly operate with the distribution grid (Hoppmann et al 2014: 1105).[9] With respect to the common pattern, it can be expected that there are smaller surpluses in mild winters, although the electricity consumption of the home, especially during sunset, is higher, which requires the use of the stored energy. In contrast, production grows in the summer and once the high consumption of air-conditioning devices has been met, the surpluses can be stored and, eventually, sold[10]. In any case, the higher the number of storage cycles, the lower the costs of storage (Rathgeber et al 2015).

3. The prosumers and the electricity market

Leaving aside the grid departure, the detailed analysis of the types of grid exchange (exports and imports of electricity) leads to the distinction of three situations:

- Regulation gives the greatest priority to self-sufficiency, that is, the instantaneous self-consumption plus the consumption which uses the previously stored energy. Therefore, if there are surpluses, these will always feed the battery.[11] Electricity will be sold to the grid only when this is full. Therefore, exports will play a marginal role (Deutsch and Graichen 2015:10), although also imports will be limited (they could even be null, as shown by Castillo-Cagigal et al 2016: 3). The economic outcome of these exchanges will depend on the volume as well as the prices of both electricity flows.
- The regulation allows prosumers to either accumulate the surplus or sell it. This decision will be taken without any influence of the state of charge of the battery, since self-sufficiency is not a priority. In this case, the sales are justified by the price perceived per kWh, although they are only allowed if surpluses are generated. Exporting electricity at an sporadically high price implies assuming the risk that, in the future, it will have to be imported at a (hopefully) lower price.[12] Differently from the previous case, microgenerators need to constantly

[8] Those inflows and outflows of electricity will lead to a given state of charge of the battery. Given the scope of the suggested model, it can be ignored.

[9] A lifetime of 8/9 years could be assumed. For the following years, much cheaper batteries with thousands of complete cycles of charge/discharge can be expected (Böcker et al 2015: 215, Bussar et al 2016: 2, Few et al 2016:19). The round-cycle efficiency of a stand-alone battery is around 80% (Hoppmann et al 2014: 1106 and 1109). Their auxiliary systems represent between 2/3 and ¾ of the total cost of the storage system (MacGill and Watt 2015: 239).

[10] For reasons of simplicity, the role of the electric vehicle as a pool and source of electricity has not been included (see, however, Mwasilu 2015 and Kaschub et al 2016).

[11] The self-sufficiency condition can be stricter if, once the battery has been charged, the surplus electricity has to feed the thermal energy storage systems, such as heat pumps which deliver hot water and heating (IEA-RETD 2014: 57, Parag 2015: 17).

[12] The reality is obviously much more complex: the prosumer has to predict the generation and consumption profile, at least for the next day. See Zong et al (2016).

receive information on (wholesale) electricity prices, which implies their connection to a smart grid[13].

- The regulation allows mPVG to freely interact with the grid. Exports and imports can take place at any time, whether there is a surplus of self-produced electricity or not. The stored electricity can also be sold to the grid. The only motivation for prosumers would be that the (sale or purchase) price is attractive at such moment. If the price of electricity is not attractive, the level of the instantaneous self-consumption will be reduced or the status of the battery will be ignored. The goal of the prosumer, who is aware of the information on prices provided by the smart grid, is to seize the opportunities. Obviously these will be commercial prosumers.

The interaction with the grid is basically a regulatory issue. To start with, it is highly likely that the degree of grid exchange (or its reciprocal variable, e.g. self-sufficiency), will be set by legal limits, e.g., a certain quantity of kWh which is prone to be bought/sold per unit of time. Secondly, the capacity of the on-site generation system will be set equal to or lower than the households or business contracted load. This restriction is justified in order to avoid further setbacks to the distribution grid. This is a requirement which may severely limit the activity of commercial prosumers, although load management may counteract this to some extent. Furthermore, the prosumer will need to comply with several technical requirements and, in some countries, he might have to bear all the grid-connection investments (deep connection rule). Therefore, it is likely that the remuneration scheme turns into net billing: there are two meters (or only one with two independent metering devices) to separately gauge exports and imports, because they are measured in monetary terms at different prices. Perhaps, the price for the exported electricity could be the wholesale electricity market or another value close to this price stemming from a specific regulation. The retail price will probably be the price paid for electricity imports.[14]

4. Costs of generation including load management, battery performance and grid interaction

Once the three possible cases of the interaction of prosumers with the grid have been identified, we can deepen the analysis excluding the mPVG with a commercial orientation. Its complexity would require a much more comprehensive analysis than the one provided in the following pages.

In addition to the previously provided notation, the following has to be considered:

w_t wholesale electricity market price, or the price received for exporting in *t*.

ε_t volume of electricity sold to the grid in *t*.

[13] The zero net energy condition has been excluded. This condition means that, at the end of the billing period, or maybe the natural year, there aren't any net electricity imports (Lacy and Buller 2012: 3), It requires an energy storage system, and the broad implementation of efficiency and saving measures (Hawkes and Hanna 2015: 284-285).

[14] There is the possibility of a net balance scheme, that is, the energy exported is banked and acts as a cap for electricity imports, which should be done in a given span of time. In principle, the exported energy flow does not receive any economic compensation at all, and the micro-generator will not have to pay for the equivalent electricity being imported. However, flows will most probably be computed and balanced in monetary terms. For this reason, the net balance scheme becomes a variant of net billing. Moreover, excess imports over exports may be purchased at retail prices.

m_t volume of electricity imported from the grid in t.

Let's consider a reference day during which, according to Figure 2, the hourly demand x is covered with five different possibilities:

- Only with imports in the intervals $[0, t_1]$ and $[t_5, T]$.
- With a mix of imports and instantaneous self-consumption between $[t_1, t_2]$.
- With instantaneous self-consumption between $[t_2, t_3]$.
- With a mix of instantaneous self-consumed energy and energy from the battery between $[t_3, t_4]$
- Only with previously stored electricity between $[t_4, t_5]$.

Furthermore, the model contains the following assumption: the stored electricity is consumed during the evening (sunset) and early night hours in the same day.[15] This probably occurs in the span $[t_3, T=24\text{ h}]$, when the domestic demand is high (as it occurs in the winter in intermediate latitudes) and the electricity produced by the panels is very low (or absent).

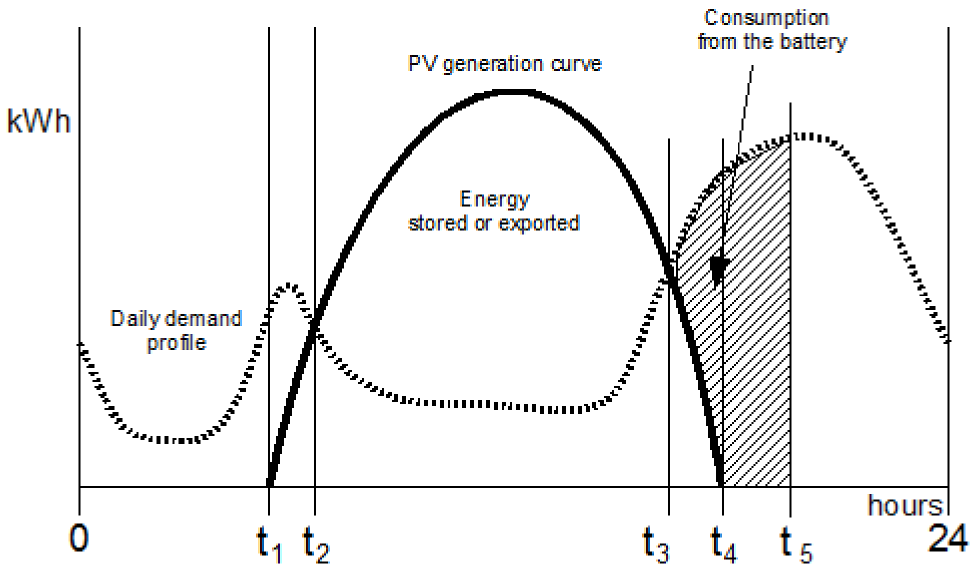


Figure 2. Load and generation profiles

Therefore, four periods of costing (per kWh) should be taken into account:

- Demand satisfied from the grid:

$$c_t^1 = \sum_{0}^{t_1} m_t \cdot e_t + \sum_{t_5}^{24} m_t \cdot e_t \qquad [1]$$

This is a realistic assumption if there is no storage of imported energy (see below).

[15] However, the model does not change if the stored electricity is consumed during the night hours and in the first hours of the following day.

- Instantaneous self-consumption starts:[16]

$$c_t^2 = \sum_{t_1}^{t_2} \left(a_G^h / q_t + m_t \cdot e_t \right) \qquad [2]$$

The self-generated energy consumed in [t_2, t_4] will be considered in brief.

- PV excess energy directed to storage or exports:

$$c_t^3 = \sum_{t_2}^{t_3} \left[a_G^h / q_t + a^h \Big/ \beta_t^+ b_t^+ + \varepsilon_t \left(a^h / q_t - w_t \right) \right] \qquad [3]$$

This expression includes, first, the cost of the self-consumed electricity. In addition, it includes the cost of storage (i.e., the daily impact of the investment in generation and storage equipment, divided by the volume of generated electricity which has been accumulated). The cost of electricity which the battery contained is ignored since this cost was already considered when the electricity was stored. The expression includes the cost of generating the volume of exported electricity (ε_t) minus the revenues from its sale (at wholesale prices).

- Load partially or totally satisfied from the storage:

$$c_t^4 = \sum_{t_3}^{t_5} \left(a_G^h / q_t \right) \qquad [4]$$

that is, the cost of generating the immediately consumed energy. This does not include the value of the discharged electricity, since its cost was accounted for when it was stored.

Then the total cost, C_t, is,

$$C_t = \sum_{1}^{4} c_t \qquad [5]$$

In this expression, the impact of load management is assumed to be included in the terms m_t and ε_t, that is, the imports would be higher and the exports would be lower without the L^M. It is also assumed that the capacities of the generation plant and the battery are optimized.

4.1. The mPVG with residual exports (or self-sufficiency priority)

With respect to the economic behaviour of prosumers with residual exports (or self-sufficiency priority) it should be considered:

- When PV plant is not generating and the battery is empty, all the consumed electricity comes from the grid.

[16] The O&M costs of the plant (generation and battery) have been ignored.

- When PV plant is on, electricity is instantaneously consumed in case of no surplus. However, in case of an electricity excess, firstly the battery is charged to full. Then, energy is exported.
- Regarding the role of load management, in this case the prosumer is not probably connected to a smart grid. He concentrates the consumption in the periods of surplus electricity (after all, $a_G<e_t$). This does not undermine the objective to charge the battery to its maximum level and to use load management rules to reduce the electricity imports.

These rules are shown in Table 2.

The goal of the prosumer is to minimize the cost of electricity consumption. To do so, the load management system has two alternatives:

- Shift of demand to the period in which the surpluses are generated.
- Using the battery to minimize imports.

Table 2. The mPVG with self-sufficiency priority

PV plant	Flows of electricity		Load management
It is generating	Electricity surplus	Exports to the grid	Load priority
		To the battery	
	No surplus	Instantaneous self-consumption	Reduction of consumption (imports)
No generation	Battery discharging until its depletion		
	Imports from the grid to be consumed		

In the first case, given that the regulation promotes self-sufficiency, equation [3] can be rewritten as follows:

$$c_t^3 = \sum_k \sum_{t_2}^{t_3} \left[a_G^h \big/ \sigma_t^k + a^h \big/ \beta_t^+ b_t^+ \right]$$

until $\beta B = b^{max}$ and, simultaneously, consumption takes place in this period as much as possible. If, despite this, there is still an electricity surplus, the value of exports will be,

$$c_t^3 = \sum_{t_2}^{t_3} \varepsilon_t \left(a^h \big/ q_t - w_t \right)$$

All in all, $w_t << a^h/q_t$, which means that such value will be a residual one. The possible revenues from exports have a subordinate role. They will probably be possible during the summer season, although they will not make up for the cost of imports when the whole year is considered.

Furthermore, for the 4th period, the following could have been written:

$$c_t^4 = \sum_k \sum_{t_3}^{t_5} \left[a_G^h \big/ \left(\sigma_t^k\right)_{LM} \right]$$

which means that load management reduces the consumption of appliances in oder to extend the use of the battery. Therefore, the imports in the next period are reduced, [t_5, 24], since its duration is comparatively lower.

4.2. The mPVG with limited arbitrage (or partial self-sufficiency)

In case of mPVG with market arbitrage constrained to the surplus electricity,

- If the retail prices are higher than self-generation cost, then the electricity provided by the PV plant is instantaneously consumed.
- If there is an electricity surplus, it could be accumulated or exported.
- If the plant is not generating, electricity could come from the battery and, when fully discharged, consumption is assured by imports from the grid.

In order to start the discussion of this case, it should be mentioned that there are many possibilies to decide the portion of surplus energy which is stored and the portion which is exported. As observed in Figures 3, part of the surplus generated between two moments (t_2 y t_3) is stored, whereas the rest is exported. More specifically, in the upper figure (3a), energy is stored in the span [t', t''], i.e.:

$$\varepsilon(t) = \int_{t'}^{t''} g(t) - \int_{t'}^{t''} x(t)$$

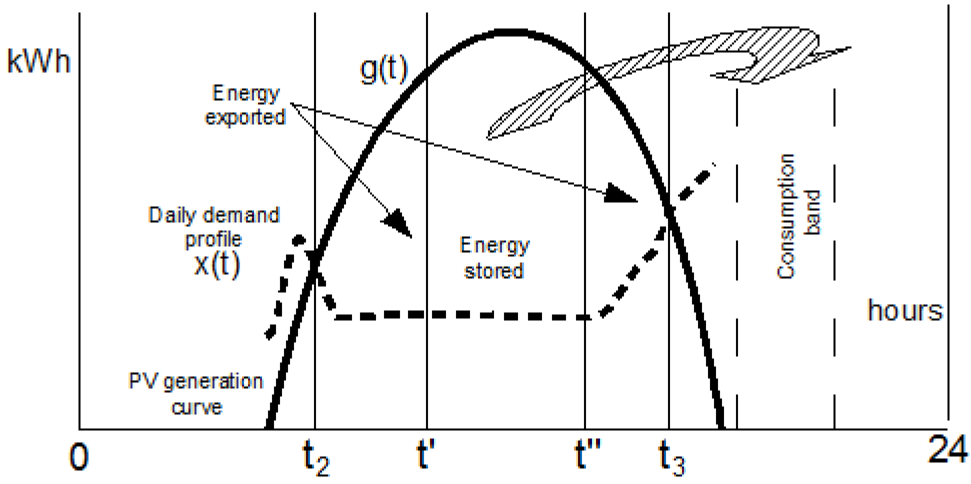
where $g(t)$ is the function which represents PV generation and $x(t)$ refers to the load. Regarding figure 3b, a functton $s(t)$ can be defined which shows the trajectory of storage in the time span [t_2, t_3], both included in $g(t)$. Therefore, the exported electricity is calculated through the following expression[17]:

$$\varepsilon(t) = \int_{t'}^{t} g(t) - \left[\int_{t'}^{t''} s(t) + \int_{t'}^{t''} x(t) \right]$$

As it can be observed, it has been implicitly assumed that the possible quantitative limits to exports, in case that they are set by regulation, are not exceeded. Furthermore, in order to simplify the model, it is assumed that:

- The house does not have a battery which is able to store electricity for several days.
- The prosumer, who is connected to a smart grid, has a device which is able to predict the retail price some hours in advance and act accordingly. It can also receive and accept, or not, anticipated offers on imports. Futhermore, the device collects and interprets instantaneous prices. This implies that the traditional flat rates have been displaced by TOU rates, which are probably highly influenced by wholesale electricity prices.

[17] In reality, however, there could be several interleaved lapses of storage/export. This has not been modeled in this paper.



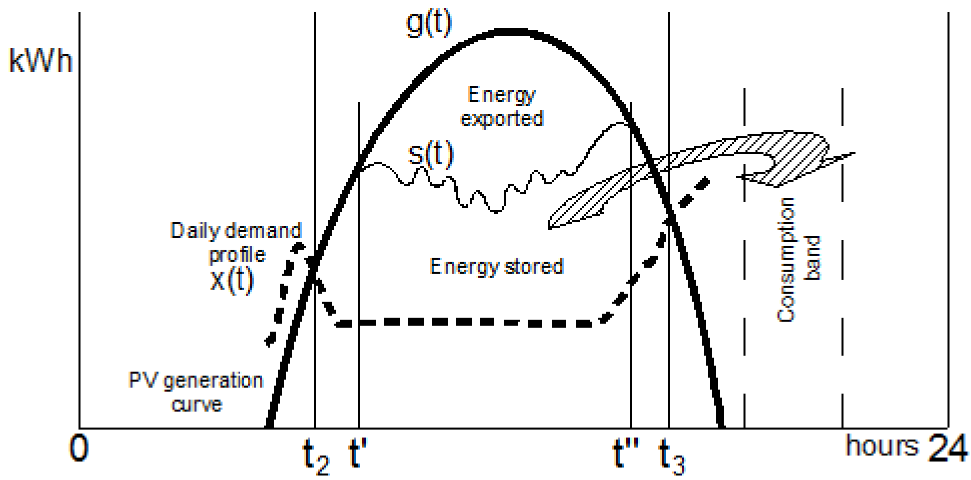


Figure 3a (up) and 3b (down). Trade-off between storage and exports

The analysis of the hypothetical behavior of the prosumer with partial self-sufficiency starts by considering that, during some hours of the day, all the self-produced electricity is instantaneously consumed, although this might be insufficient in order to cover the demand, which requires imports. These are unavoidable during the first part of the day when, if the battery is still charged, it will be completely emptied. When the PV plant generates a surplus, this will be deviated to the battery if $w_t < a$, whereas the electricity is exported if $w_t > a$. However, if $e^*_t < e_t$, that is, if the initially expected retail price (e^*_t) is higher later (in the hours when the electricity needs to be imported), then the revenues from the daily sales to the grid lose their capacity to offset the imports.

The on-line information on the electricity market prices endorses the decision to either divert the surplus to the battery or to sell it to the market. However, the relevant price is not only the current one, but also the expected import price. If the forecast indicates relatively higher retail prices at sunset, electricity consumption can be shifted to the central hours of the day, even if this reduces exports. However, there might be forecast errors and, thus, the expected programming for the load management would be counterproductive. Indeed, the greater is w_t, the more onerous will be the restriction of exports due to load management. The final result will depend on the interaction between quantities and prices.

In the case of the prosumer with partial self-sufficiency, the really important criterion to take a decision is given by the difference between C_t and C_t*, that is,

$$C_t^* - C_t = \sum_{t_3}^{T} (m_t e_t^*) - \left[\sum_{t_3}^{T} (m_t e_t) + \sum_{t_3}^{T} \frac{a^h}{\beta_t^+ b_t^+} + \varepsilon_t \left(w_t - {a^h}/{q_t} \right) \right] > 0$$

where C_t* is the initially expected cost and C_t is the cost which results at the end of the day. In this expression, the first term reflects the expected cost since the surplus disappears until the end of the day (a prediction which may or may not be accurate). The second term indicates the real cost of those imports. The third term shows the cost of recharging the battery (which might be null, if there isn't any recharging). The last term indicates the net revenues due to exports. Obviously, the expenditure before the possible surpluses appears in both sides of the equality and, thus, it has been removed.[18] If we simplify and reorder the terms, then:

$$\sum_{t_3}^{T} w_t (e_t^* - e_t) - \frac{a^h}{\beta_t^+ b_t^+} - \varepsilon_t \left(w_t - {a^h}/{q_t} \right) > 0 \qquad [6]$$

The prosumer tries to achieve a value as greater as possible in [6], which implies that the real retail price was clearly lower than expected, which justifies the exports in the previous hours. This is in spite of their generation and storage cost and the fact that, the lower the amount of electricity being stored, the more expensive will be this operation. Unfortunately, the negative impact of those factors has been overshadowed in [6]. However, achieving a positive value at the end of the billing cycle (or, better, for a whole year) does not seem to be easy.

5. Discussion

Both mPVG plants comply with the well-known avoided cost principle: the generation cost and storage, i.e., the addition of the initial investments, O&M expenditures and load management equipment, and the effects of support schemes, especially those referred to the grid exchanges, has to be below the expenditure on the same volume of electricity at retail prices during the whole lifetime of the plant (*T*) (Hughes 2005: 4).[19] In this point, the expected cost trends of systems used in mPVG look promising: the batteries and auxiliary equipment will reduce their prices and, hence, the cost of kWh is estimated to be in the range of 5 to 10 €cents/kWh. This number, which includes the cost of panels, may be competitive with the retail electricity price in many places, particularly in the sunniest ones.

The second general assumption is to consider doubtful that residential prosumers invest looking for a high profitability. Their satisfaction seems to be related to three aspects: to

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[18] In this expression, the impact of load management measures is not explicit since it is behind the factors which affect m_t and ε_t.

[19] This is a clear criterion, but subject to uncertainty: the lack of knowledge of future electricity prices. Moreover, it should be taken into account that some devices, such as the inverter and the battery, have an operation lifetime shorter than the lifetime of the PV modules. This fact should be included in the calculation of plant depreciation (Quoilin et al 2016: 63).

achieve autonomy with respect to the distribution grid and its problems (Gärhs et al 2015), to gain social prestige (showing environmental awareness), interest for the technology etc. (IEA-RETD 2014: 29) and to achieve substantial savings with respect to purchases of electricity at retail prices.

Given all these expressions, for the prosumer whose priority is self-sufficiency load management has the goal to extend the period over which the battery meets own electricity demand. In temperate zones, during the cold sunsets a careful programming of the battery and load management will be needed in order to avoid relatively expensive imports. According to the previous cost expressions, this leads to comparatively higher values for c_t^4 and comparatively lower values for c_t^5. The final result is a lower overall cost since $a<e_t$. The revenues as a result of exports should also be taken into account. However, it is likely that their possible increase is negligibe, since they are paid at wholesale electricity prices and self-sufficiency is the priority of the prosumer.

The prosumer with partial self-sufficiency will have to schedule the exports as a function of the expectation of the evolution of retail prices (for the sunset in the same day). This claim makes sense in a context in which,

$$e_t > {a^h}/{q_t} \lesseqgtr w_t$$

that is, the retail price is always above the generation and storage costs, whereas the wholesale price may be above ${a^h}/{q_t}$ during some time spans.

It is assumed that the electricity is purchased at current retail prices. This energy might be dedicated to meet immediate consumption (at a cost of $m_t \cdot e_t$) or to charge the battery. This storage operation has a cost of ${e_t}/{\beta_t^+ b_t^+}$. The possibility to import electricity to charge the battery depends on the structure of tariffs. If they are flat, it is likely that the retail prices are above the cost of generation plus storage and, thus, such imports would not be justifiable in economic terms. However, if there are TOU tariffs, then importing cheap electricity at night hours can be a good option, since this would lead to a greater surplus the next day which can then be exported (Ven et al 2012).[20]

6. Conclusions

The model presented represents a first analysis of the economic effects of the combination of the four subsystems which make up a mPVG plant: the generator, the battery, the load management devices and the grid connection. Despite its simplicity and its merely conceptual character, the model allows us to infer the following conclusions:

- The mPVG plants are complex technological systems. It will be not easy to optimise its design. The relationships between the main variables could be not linear and they are affected by many technical details. Notwithstanding, regulators and experts will be probably able to develop protocols, to implement rules and create typologies to make the realization of projects easier.

[20] After a few hours, the surpluses which have been generated at a cost of $a^h_G/q_t << e_t$, will allow to partially recover the charge.

- The complexity of everyday use should also be considered. If the interface is not easy, energy citizens will opt to continue as simple consumers. It will be crucial to develop standards and introduce simple codes in order to manage the mPVG plants (Bradbury et al 2016: 36). In the case of self-sufficiency as a priority, load management contributes to the objective, even opening the door to grid departure. It is not difficult to imagine automatic systems which appropriately adjust the activity of shiftable appliances. The case of mPVG with limited arbitrage is much more demanding: we have to take decisions on future prices, which leads to a set of decisions regarding load management and the use of battery. Although it is a forecast for the next few hours, it seems difficult to imagine that individuals will add this responsibility to the ones they have in their ordinary lives.
- Inducing the participation in the electricity market of the prosumers under a partial self-sufficiency regime will probably confer to the aggregators a key role.
- Regulatory details related to the design of microgeneration tariffs may only delay, but not remove, the incentive to deploy mPVG. Many obstacles may arise in order to hinder the diffusion of mPVG plants: the removal of any support measures for prosumers (subsidies, rebates, etc.), exports might not be remunerated or specific charges for the self-consumed electricity or for being connected to a smart grid might be applied. All in all, the reduction in generation costs will end up being more relevant than all of them.
- It has often been considered that the most relevant topic is to decide whether residential or commercial microgeneration should have the objective of reaching the maximum self-sufficiency contribution to self-relief (Schill et al 2017: 24), or if it is more relevant to encourage its maximum contribution in order to reduce the peak demand of the electricity system. It is too simple and increasingly obsolete to imagine the future of micro-generation only considering the disadjustment between intermittent generation and rigid demand needs. There is an increasing analysis of the services that the prosumers may provide (under remuneration) to the electricity system. Although the details have only been superficially addressed (Bronski et al 2015, Fitzgerald et al 2015, Bradbury et al 2016: 34), it is clear that the prosumers may participate in the ancillary services, including load following or frequency regulation, etc. The battery fleet of prosumers could help to guarantee a reliable and predictable supply.[21] Given that the diffusion of mPVG requires value-creation for prosumers, the implementation of specific markets and their contribution to ancillary services will be an important issue. It is yet to be known whether mPVG plants whose role is sulf-sufficiency (or with residual exports) may have a sufficiently preeminent role in this regard.
- The impact of social factors in the mPVG is a subject worth to be analyzed. For example, the size of families, the impact of lifestyle, etc. Regulation will also need to address the intricate issue of changes in the ownership of the dwelling which can lead to changes in the generation or storage capacity.

[21] It should also be analyzed if the prosumers can be compensated for grid deferral, taking into account that the capacity of the grid is determined according to peak-demand.

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