Towards the nearly zero and the plus energy building: primary energy balances and economic evaluations

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ABSTRACT

In the construction sector, responsible of the greatest amounts of energy consumption and greenhouse gas emissions, nowadays a significant turning point in the current scenario that qualifies building approach is taking place. In recent years, the ambitious *nZEB* (*nearly Zero Energy Building*), a building with very high energy performance, in which energy saving, cost-optimal vision and user well-being are assessed in a comprehensive way, has found legislative and operational implementation. Moreover, the adoption of increasingly challenging energy targets today offers important opportunities for the energy requalification and improvement of the overall quality of the building stock, particularly in the field of renewable plants.

Within this frame in the paper, as a contribution to the analysis of benefits deriving from the use of *RES* (Renewable Energy Sources) plants in buildings, in terms of primary energy, cost, and greenhouse gas emissions, an intervention aimed at the satisfaction of the electric demand of a residential building through a photovoltaic plant, in different configurations (grid connected, stand-alone and storage on grid) has been analysed. For each configuration, balances between energy rates (production, load, grid exchange and/or battery store/withdrawal) have been hourly assessed in order to evaluate the *Net Present Cost* at the end of plant life.
Moreover, a yearly primary energy balance has been determined, taking into account also thermal energy required to guarantee thermal needs (provided by a methane boiler), together with produced CO_2 emissions.

Keywords: nZEB, renewable energy source, solar energy, photovoltaic, storage

1. INTRODUCTION

In the next future a new sustainable and distributed energy paradigm should be established, mainly based on micro-generation from RES, energy storage, nZEBs, smart grids and electric mobility.

Concerning the use of RES, many authors have written about this issue. [1] presents a snapshot of diverse energy topics from bioenergy and biogas, storage, district heating and carbon emissions within the framework of sustainable development; in [2] Narayanan et al. investigated whether it is possible to cost-effectively employ 100% RES to produce electricity to meet cities' loads or partial loads; in [3] a statistical methodology with a hierarchical cluster analysis of regional typologies, according to energy consumption and deployment, develops administrative tools to draw decisions in planning energy policy in Greece; in [4] a conceptual framework and a mathematical model is introduced to simulate the time evolution of the energy balance of energy conversion technologies in order to choose the best option; in [5] it is discussed how to overcome some institutional barriers met when radical technological changes, such as the replacement of fossil fuel with renewable energy, are to be implemented; in [6] the technological change towards cleaner energy technologies developed in Denmark is described, together with the difficulties and challenges arisen; in [7] two different shading effects on energy production of a PV generator, respectively originated by tilted strings and projected by an adjacent tower building, have been analysed; in [8] interaction between intermittent RES supply and energy demand is discussed.

Due to the necessity to overcome intrinsic intermittency of most RES, energy storage is today one of most discussed arguments. Different storage techniques of both thermal and electric energy are presently studied: [9] develops a simulation model for the optimization of an autonomous RES system, incorporated in design of combined heat and power generation, where thermal and electrical loads are met utilizing photovoltaic-thermal panel, wind turbines, thermal and electrical energy storage and electric heater; in [10] a multi-objective optimization of batteries and hydrogen storage technologies for remote PV systems is presented, minimizing the total levelized cost while fulfilling consumer satisfaction; in [11] a system aimed at hydrogen production through electrolysis from RES (provided by both PV and wind generators), its storage and reconversion in fuel cells is presented, the energetic simulation of which is reported in [12]; in [13] an analysis of financial mechanisms in support to new pumped hydropower storage projects in Croatia is presented; [14] evaluates a thermal energy storage system, using different Phase Change Materials, to recover for other applications waste thermal energy released in industrial processes; [15] examines the impacts of compressed air energy storage in a pool based wholesale electricity market.

Particularly referring to the construction sector, UE Directives address towards the ambitious nZEB [16], a building with very high energy performance, in which energy saving, cost-optimal vision and user well-being are assessed in a comprehensive way: in this frame the building is required both to markedly reduce primary energy consumption and greenhouse gases emissions, guaranteeing high levels of living comfort, with a view to economic and financial optimization.

Concerning nZEB, [17] presents a review on the technological developments in the essential items supporting the integration of successful nZEB/PEB (plus energy building), i.e. accurate simulation models, sensors and actuators and building optimization and control; [18] contains a review of most ZEB definitions and of the various approaches in ZEB calculation methodologies; [19] proposes a simplified monthly net balance as compromise between two major types of balance, namely the import/export balance and the load/generation one; [20] investigates the potential energy savings in an existing Mediterranean multi-story building, in order to achieve net-zero energy as a solution to increase fossil fuel prices; [21] takes an overall energy system approach to analyse the mismatch problem of zero energy and zero emission buildings; [22] summarises the findings of a cross-comparative study of the societal and technical barriers of nZEB implementation in seven Southern European countries; [23] investigates the potential energy savings in an existing multi-story building in the Mediterranean region in order to achieve net-zero energy; [24] discusses the recent progress in nZEB research and practice, in the sections: concept definition, policy instruments, demonstration buildings, design strategies and technologies; [25] investigates in which conditions and extent a significant imbalance of energy needs (for heating and cooling) occurs in different building types and climatic zones; [26] focuses on the design, testing and construction research necessary to develop an innovative adaptive building envelope with smart materials and novel technologies; in [27] an energetic, economic and environmental analysis of two different configurations of a self-sufficient system for energy production from renewable sources in buildings is presented.

Particularly concerning primary energy reduction, a large number of studies is present in literature: [28] illustrates the results of the data collected on voluntary participation, on building characteristics, energy performance, efficiency measures and energy savings, from more than a thousand new and existing European non-residential buildings of different age, size, use and type (offices, hotels and industry), in which owners accepted to adopt energy efficiency measures to decrease energy consumption by at least 25%; [29] describes the results of experimental tests and simulations evaluating the performance of an electrochromic window with respect to solar radiation control and the relative impact on energy consumption of residential Italian buildings; [30] reports an analysis aimed to optimize the glazed surface in order to minimize energy consumption in an Italian office building, as the climate, the envelope thermal features and the lighting electric power vary; [31] evaluates the possible energy saving solutions to reduce energy demand in health facilities.

As to emission reduction consequent to energy saving measures, [32] analyzes the causal relationship between CO_2 emissions and energy consumption within a panel vector error correction model; [33] estimates emissions in Emirates for a baseline of future possible scenarios towards transitioning single-family households to low and eventually near-zero operational carbon emissions; in [34] a completely autonomous, zero-emission photovoltaic-based system is modelled for residential applications, integrated to an electrolyser-hydrogen storage-fuel cell subsystem to fully fulfill a varying load profile throughout the year; [35] describes an experimental study about indoor/outdoor air pollution in the urban centre of Messina (Italy).

Regarding comfort conditions subsistence, in [36] a simple approach to the indoor environmental quality classification is presented, proposing a methodology aimed at classifying indoor environments referring to comfort conditions; in [37] extensive field surveys in three airport terminal buildings in UK are presented, monitoring indoor environmental conditions and conducing simultaneous structured interviews in the aim of reducing energy use without compromising comfort conditions; in [38] a study is designed in which occupants in residential apartments had different degrees of personal control over heating systems: considerable differences in thermal comfort were observed, although occupants experienced quite similar comfort-related thermal parameters; in [39] an original equation for the assessment of the plane radiant temperature in presence of solar radiation is proposed, to be used for radiant asymmetry and local thermal discomfort evaluations; in [40] a development of Fanger's model is presented, embodying users' preferences referring to the cognitive–emotive–relational ambit in an algorithm using a particular multi-agent.

Finally, as concerns the economic optimization of energy efficiency measures, in [41] the cost optimal methodology indicated by the 2010/31/EU Directive is applied on a social housing building as a supporting decision tool for refurbishment interventions on existing residential buildings; [42] discusses how to describe and take advantage of people's behaviour in building thermal-energy assessment issues.

From the above it follows that energy efficiency measures, both applied to the building envelope and the technical plants through the use of renewable energy resources, are urgently required in order to achieve the described global ambitious objectives [43-45]. In Italy energy efficiency is the priority of the *National Energy Strategy* (*NES*), aimed at overcoming EU objectives to 2020, setting a final energy saving of 24% compared to the European reference scenario, to be

achieved, in the construction sector, thanks to the adoption of increasingly challenging energy parameters and thermal characteristics (minimum transmittances, yields, performance indices) and integration of renewable sources plants.
The potential savings obtainable from the civil sector are 39.7% of the national energy needs in end-use and 36% of greenhouse gas emissions, a priority target for the country together with the transition to nZEB, to be pursued by activating a wide range of regulation and incentive measures [46-47].

Researches on the matter are conspicuous: in [48], assessing the insulation features of various structures made up of totally natural and biocompatible materials; [49] describes the design and the application stage of a smart energy audit system, integrated within building, and the methodologies adopted for the detection of malfunctions of the plant; in [50] *Building Future Lab,* a great infrastructure for testing advanced building performance, a technological innovation created by the *Mediterranea* University of Reggio Calabria, is presented; [51] describes a simplified tool based on a resistance-capacitance thermal model able to represent the envelope thermal inertia, aimed at evaluating, controlling and managing heat energy fluxes in buildings; in [52] the possibilities of environmental control of smart windows with electro-chromic technology are investigated; [53] analyses the performance of an experimental prototype of a dual source heat pump system, composed by a common air-to-air heat pump and a geothermal closed loop; in [54] the load capacity of smart materials in the application to the construction sector is described.

Finally, also in the sector of electric mobility a marked contribution to EU sustainability objectives can be given: [55] is a review paper that focuses on the simulation of non-automotive and off-highway vehicles and discusses the differences in the approach to drive cycle testing and experimental validation of vehicle simulations; [56] analyses, from both the economic and environmental point of view, the effectiveness of a collective transport system, powered by renewable sources, directed to the *Mediterranea* University of Reggio Calabria; [57] reviews the feasibility and impacts of all stages from production to final use of hydrogen as a resource for mobility purposes, approaching technological, economic and environmental issues.

Within this frame in the paper, as a contribution to the use of RES in buildings and the assessment of their benefits in terms of primary energy, cost, and greenhouse gas emissions, an intervention aimed at the satisfaction of the electric demand of a dwelling through a photovoltaic plant in different configurations (grid connected, stand-alone and storage on grid) has been analysed. For each configuration, balances between energy rates (production, load, grid exchange and/or battery storage) have been hourly assessed, evaluating the *Net Present Cost* at the end of plant life.
Moreover, taking also into account thermal energy required to guarantee thermal needs, provided by a methane boiler, a yearly primary energy balance has been determined, together with CO_2 emissions produced.

2. CASE STUDY

The case study analyzed refers to a single-unit dwelling for residential use, in reinforced concrete, located in the city of Reggio Calabria (Southern Italy), characterized by a temperate climate and global irradiation of about 1'700 kWh/year on the horizontal surface, the monthly values of which, taken from ***PVSol*** software, are shown in Figure 1.

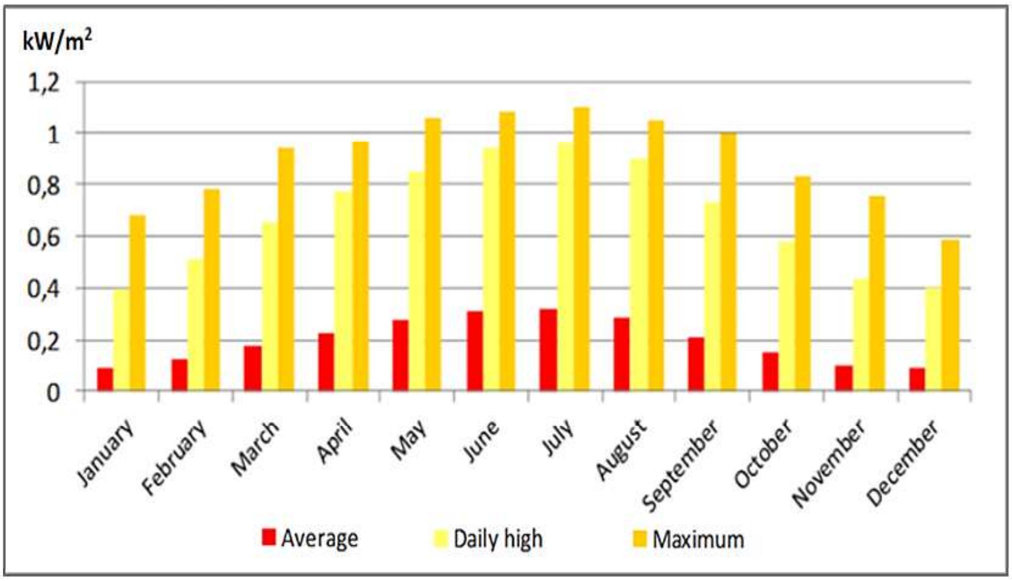

Figure 1. Average solar radiation on a horizontal plane in Reggio Calabria

The thermal demand of the dwelling is satisfied through a boiler system, using methane as energy source, while its electric consumption is guaranteed by a connection to the electric grid (Case 0). The electric load is mainly due to lighting, household appliances and, in summer season, air conditioning systems for cooling purposes and it has been simulated using the ***PVSol*** software, which outlined the hourly load profiles of the individual users, starting from their powers and operating hours. An annual load of 3,942 kWh has been estimated and compared to a realistic case from a user's bill. The monthly rates of the load are reported in Figure 2, in which it is possible to observe the demand peak in summer months due to air conditioners functioning.

The annual methane consumption (959 m^3) has been instead deducted only from the user's bills, because PVSol could not help to predict or simulate methane consumption; the corresponding thermal energy required to meet the load is obtained multiplying such volume by the calorific value provided by the distribution management (9.6 kWh/m^3), obtaining a value of 9,206 kWh/year.

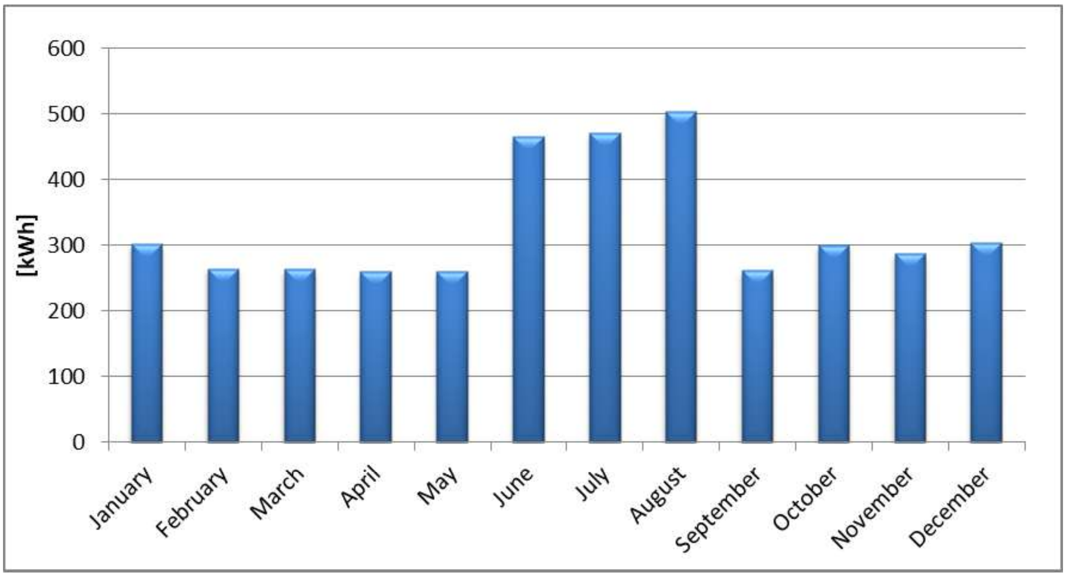

Figure 2. Monthly load

In order to reduce the use of conventional sources in favor of solar energy, the user electrical requirements have been met through different PV plant solutions:

1. *Grid Connected*: PV plant connected to the grid, no storage
2. *Storage on Grid*: the same PV system as case 1, flanked by a battery system
3. *Stand Alone:* PV plant of greater power than the previous two, in which the load is exclusively guaranteed by the PV generator and the batteries
4. *Smart Grid Connected* PV system, connecting in a *smart* way the user to a second one (a commercial activity with a complementary load), both served by a same system with total power equal to the sum of the individual ones, exchanging between users the respective production redundancies before sending them to the grid; the system was then compared to the sum of two individual plants.

PV panels are in polycrystalline silicon, with an efficiency of 14.8%; the inverter for the conversion DC/AC is a pure sine wave one, with a 3.3 kW power, assessed on the basis of maximum absorption; batteries have a gel electrolyte, a nominal voltage of 4 V and a nominal capacity of 1'900 Ah (7.6 kWh): an acid control valve allows long duration (average lifetime over 10 years), with no maintenance.
The software ***PVSol*** made the sizing of the system configurations, providing the number and arrangement of the panels, as well as the wiring diagram, starting from the load and the irradiation data.

3. ENERGETIC ANALYSIS

Starting from load hourly values referred to a monthly average day, an hourly energy balance between load, production and grid/battery exchange has been calculated in the daytime hours, estimating in the night ones energy flows from grid or battery; for this latter, the charging condition has also been calculated. The electricity rates (produced, self-consumed, fed into the grid and withdrawn from it, stored or taken from batteries) were obtained from simulations performed through ***HOMER***, a software developed by the *National Renewable Energy Laboratory* (USA). Moreover, a primary energy balance has been determined, converting into primary energy the electricity rates annually withdrawn from the grid and exported to it, together with thermal energy required to cover thermal demand.

3.1 Case 0 (*Grid connection - no PV system*)

A simple connection to the electric grid is present. Considering the residential use of the building and its electrical load, a connection to 220 V with 3 kW power has been used.

3.2 Case 1 (*Grid Connected*)

The electric scheme of the system provided by the software *PV Sol* is reported in Figure 3, where the generator power equal to 2.88 kW_p has been derived to properly satisfy the load, starting from the knowledge of the equivalent hours of the site (1,752 h). Having chosen modules with a PV power of 240 W, their total number is 12. Table 1 reports the load and the energy rates (inverter output, self-consumed, grid income/withdrawn) for a yearly period. It is:

Energy production = Self-consumed energy + grid income *Load = Self-consumed energy + grid withdrawal*

Figures 4 and 5 show both the load and PV plant production, respectively on a daily and monthly scale, Figure 6 shows the incoming and outgoing energy flows together with the self-consumed energy, while Figures 7 shows the production rates.

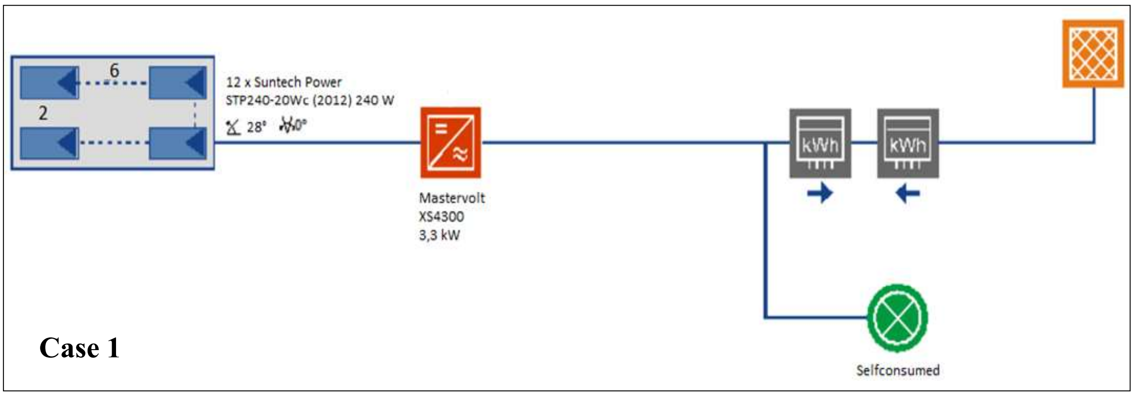

Figure 3. Electrical scheme of the plant for case 1

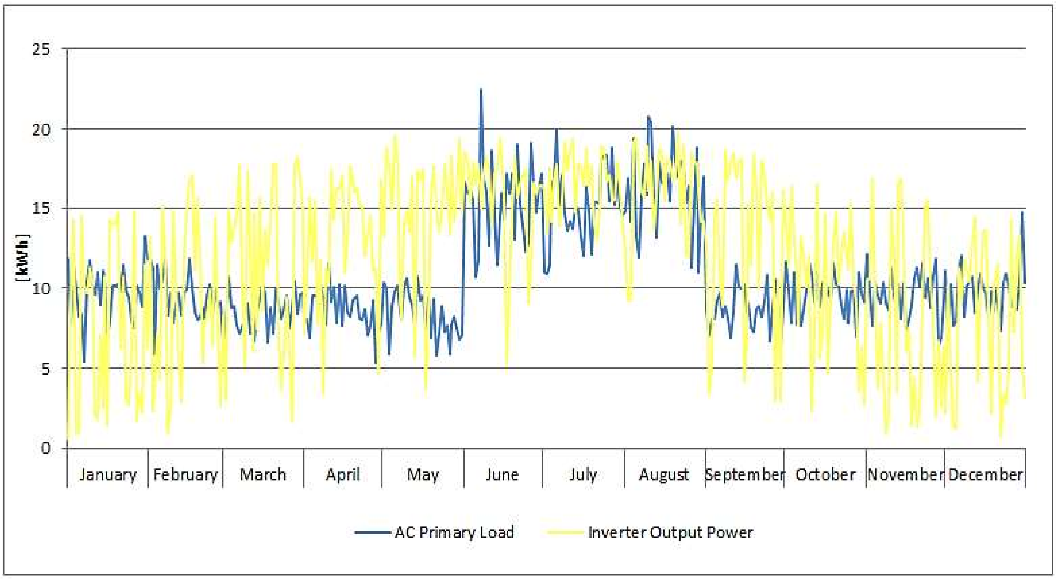

Figure 4. Daily load and PV plant production (case 1)

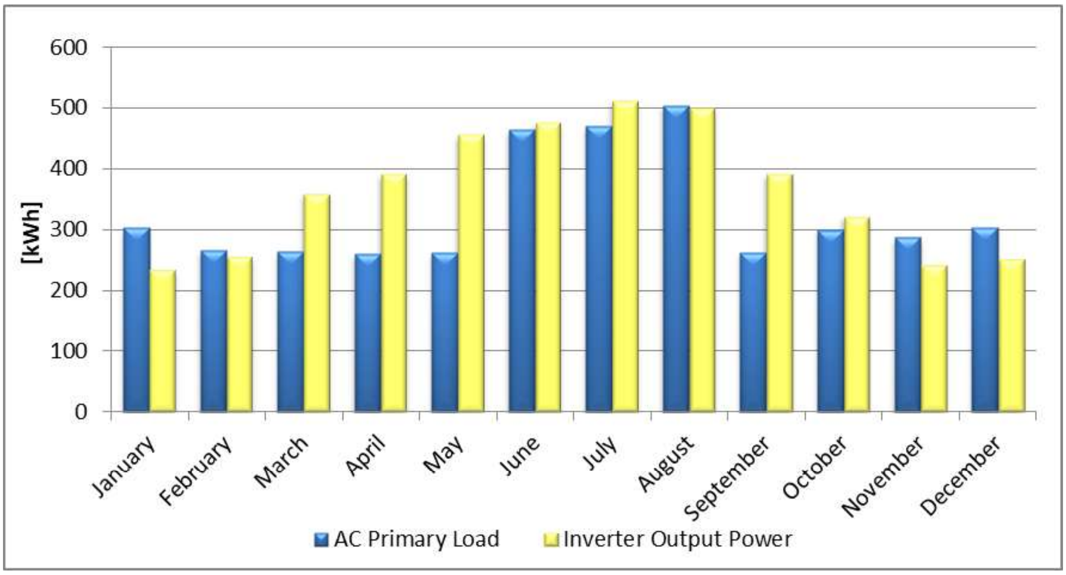

Figure 5. Monthly load and PV plant production (case 1)

Table 1. Load and PV plant energy rates (case 1)

Yearly Energy (kWh)	
Load	3,942
Inverter output	4,389
Self-consumed energy	1,364
Grid sales	3,025
Grid purchases	2,578

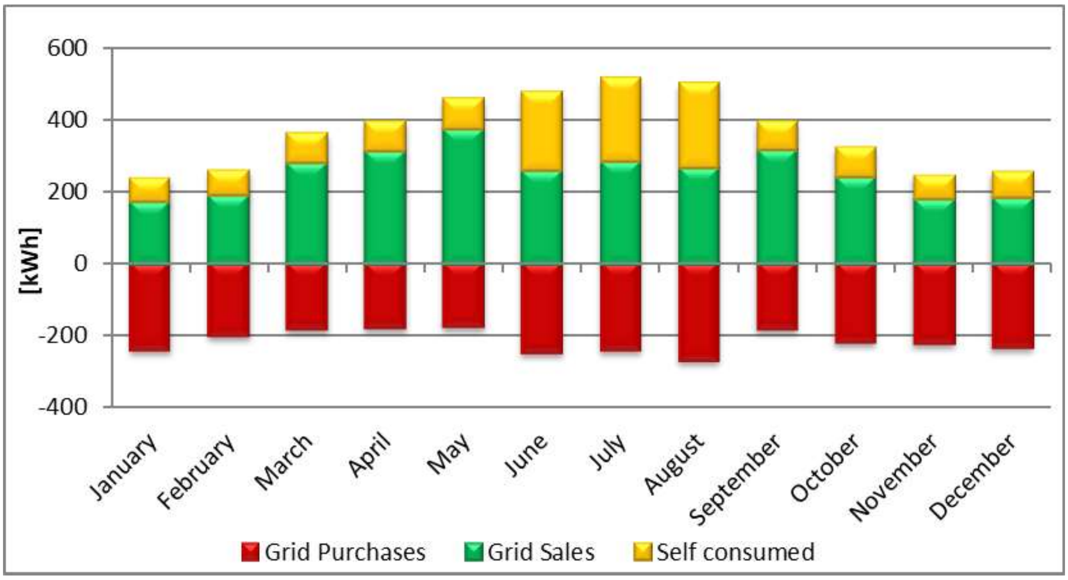

Figure 6. Self-consumed PV production, withdrawn energy and exported one to the grid (case 1)

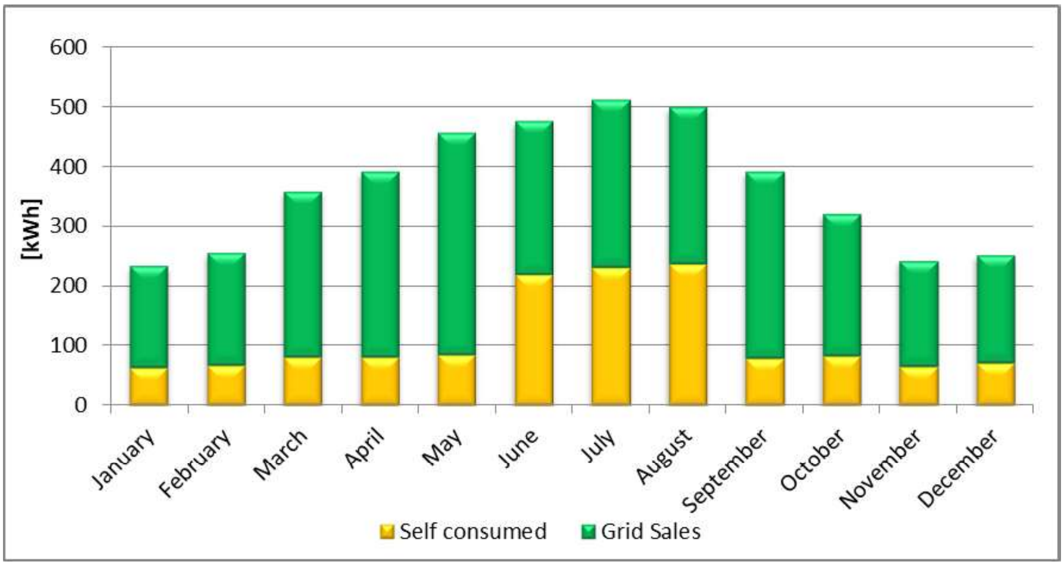

Figure 7. Self-consumed PV production and energy exported to the grid (case 1)

3.3 Case 2 (*Storage on Grid*)

The electric scheme of the system is reported in Figure 8. It has the same power as in case 1, but the grid is used only to satisfy peak demand, not covered by batteries, avoiding the system over-dimensioning (as in stand-alone configurations). The surplus energy higher than the battery capacity is introduced into the grid; energy lack, corresponding to a battery state of charge lower than its minimum capacity, is withdrew from the network. Priority is given to injecting and withdrawing energy from the battery before turning to the network, using in order self-produced and stored energy, and in the event of a production lack, energy is taken from the grid.

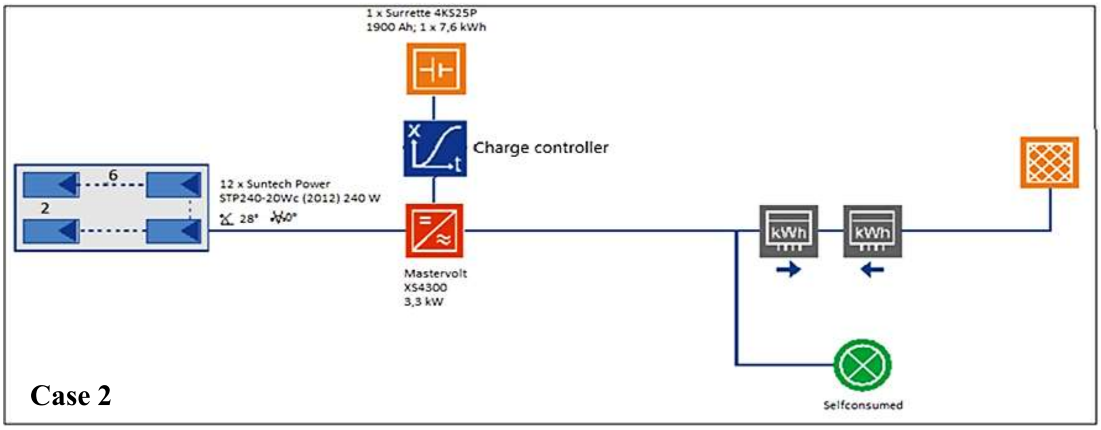

Figure 8. Electrical scheme of the plant for case 2

The load and the energy production are the same of the grid connected case, while the incoming and output energy flows are reduced for the presence of the battery. Table 2 reports the load and the energy rates (inverter output, self-consumed, taken from the battery, fed into the grid and withdrawn from it). It is:

Energy production = Self-consumed energy + battery income + grid income

Load = Self-consumed energy + battery withdrawal + grid withdrawal

Table 2. Load and PV plant energy rates (Case 2)

Yearly Energy (kWh)	
Load	3,942
Inverter output	4,389
Self-consumed energy	1,364
Battery withdrawal	949
Grid sales	833
Grid purchases	1,629

Figure 9 shows the incoming and outgoing energy flows, Figure 10 shows the load rates whereas Figure 12 reports the production ones: the lower exported rate with respect to case 1 for the presence of energy stocked in battery can be noticed.

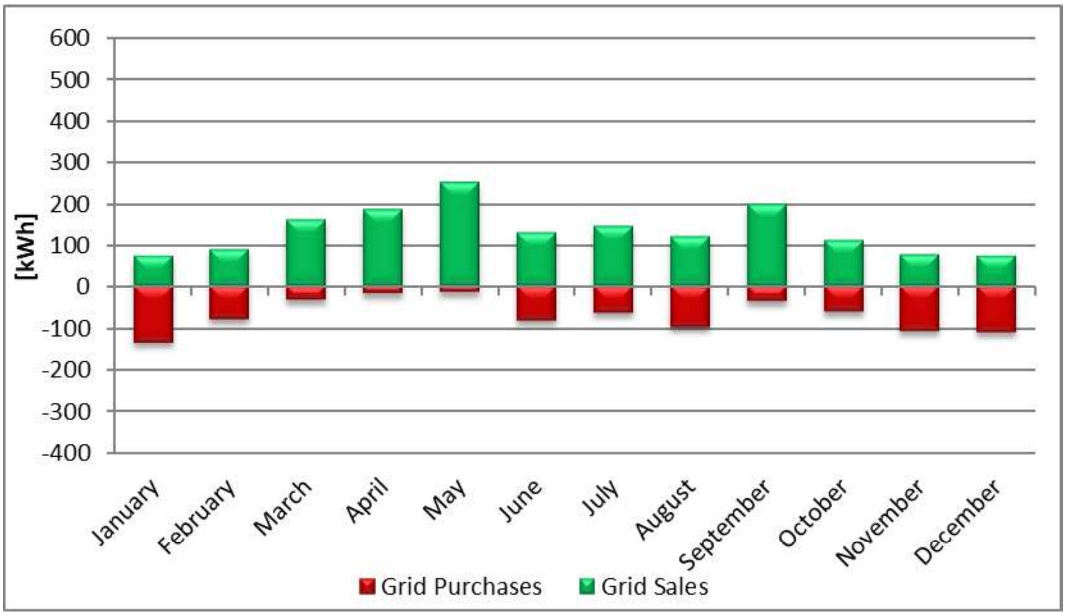

Figure 9. Energy monthly exported and withdrawn from the grid (case 2)

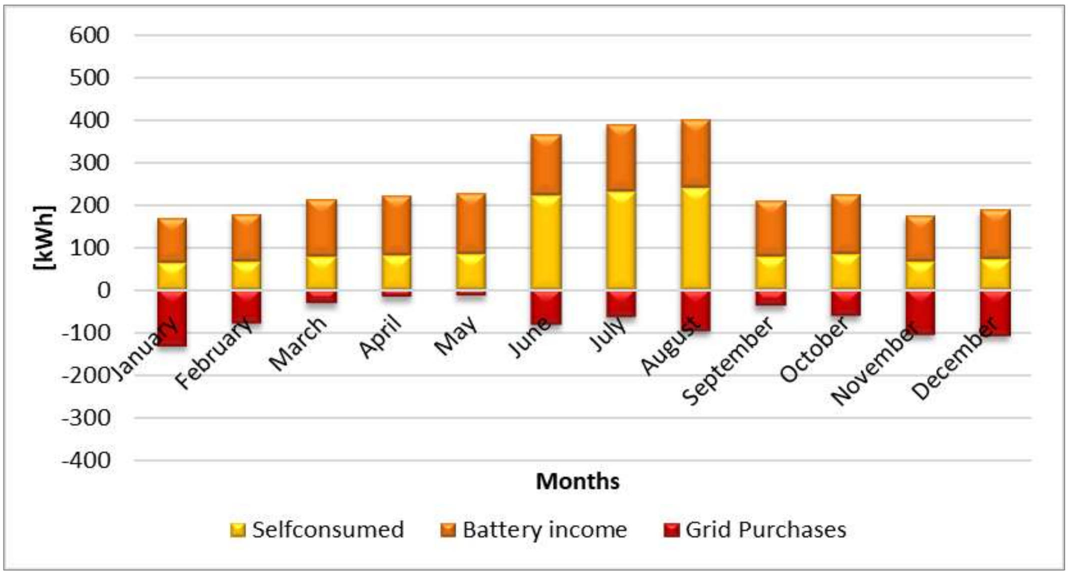

Figure 10. Self-consumed PV production, energy withdrawn from the grid and battery withdrawal (case 2)

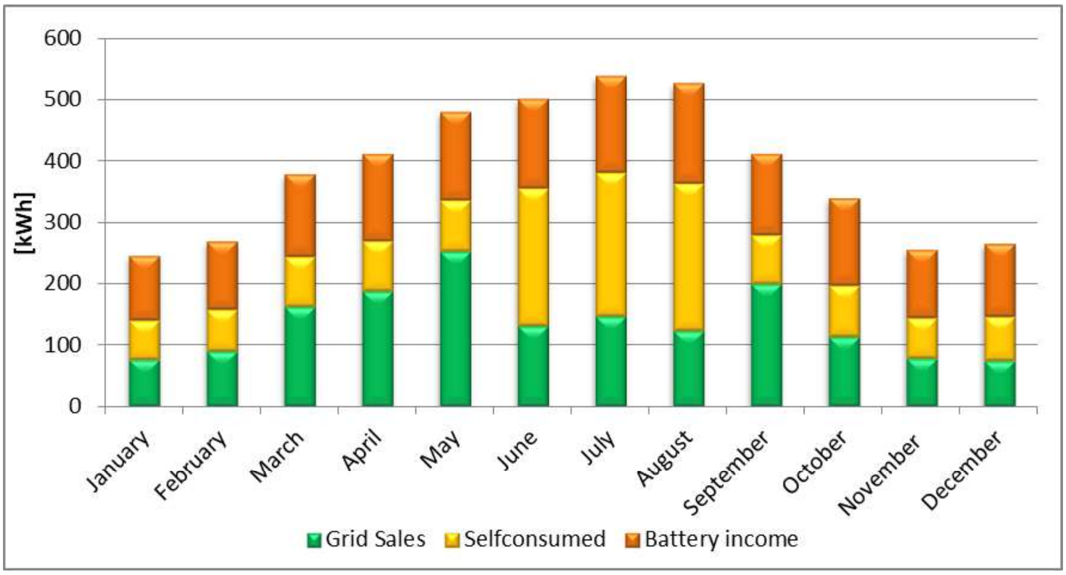

Figure 11. Self-consumed PV production, battery income and energy exported to the grid (case 2)

In order to highlight the differences existing in the extreme periods of the year, i.e. the months of summer and winter solstices (June and December), Figures 12 and 13 report cumulative grid inputs and outputs in the 24 hours of the respective monthly average days. Even during the months with high energy production (such as June), there is the necessity of withdrawing energy from the grid, being the energy stored in the battery not sufficient to satisfy the night load, while in the daytime hours also in December an amount of energy exceeding the storage capacity is sent to the grid.

The storable energy was calculated, adding it to the one already presents in the battery, assuming a 100% charge as a starting point and a 20% charge as maximum discharge. In Fig. 14 it is possible to appreciate the trend of the battery state of charge during the months of June and December: in both months it is evident that the charge reaches, almost at each discharge cycle, the minimum value of 20%; moreover, in December days in which the battery is deeply discharged are present (i.e. 5-7).

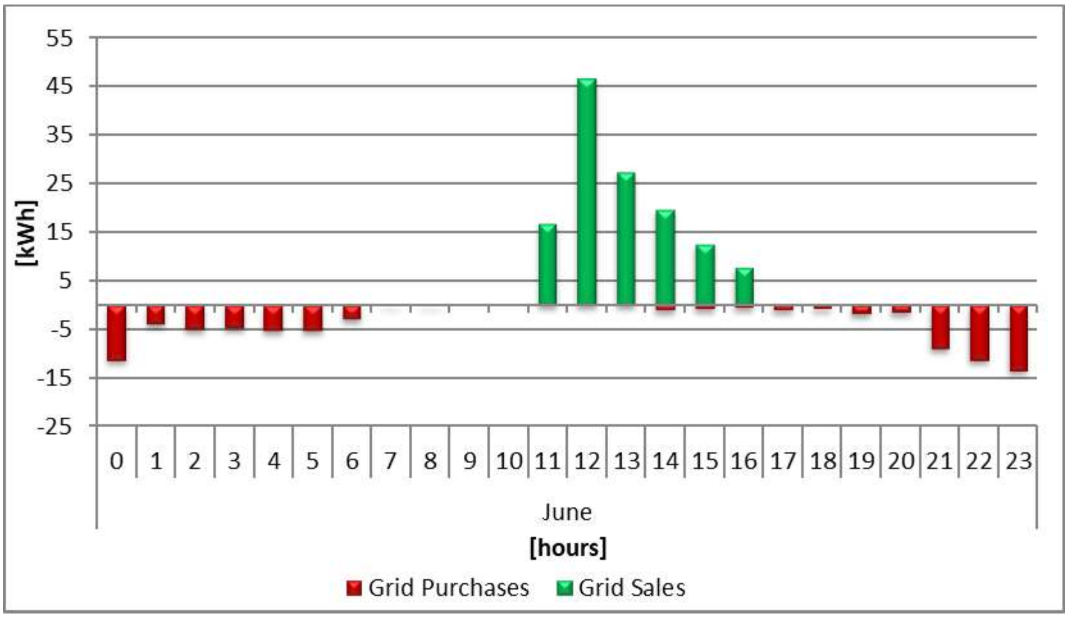

Figure 12. Energy fluxes withdrawn and exported to the grid in June (case 2)

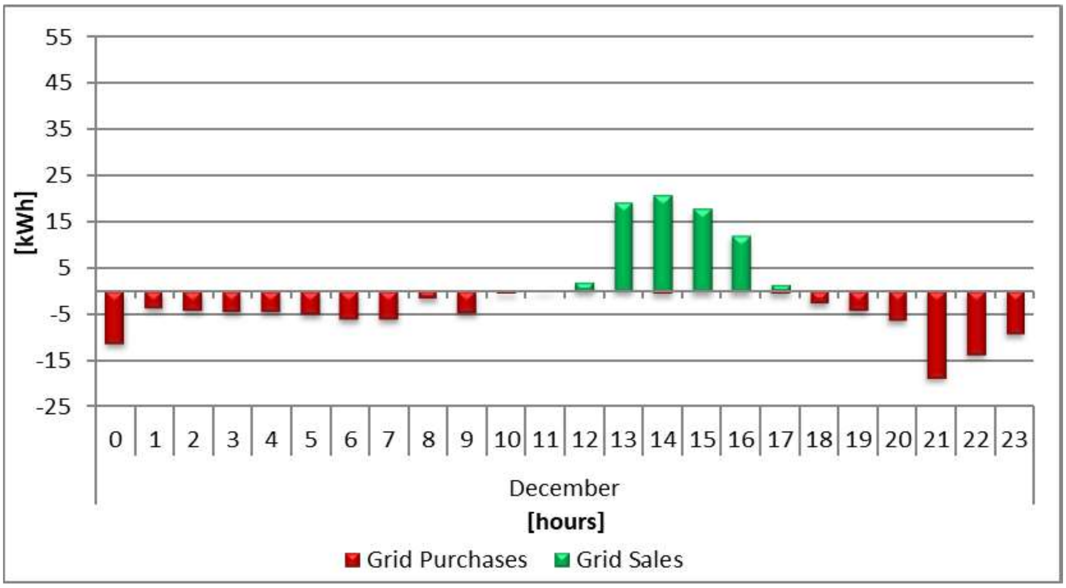

Figure 13. Energy fluxes withdrawn and exported to the grid in December (case 2)

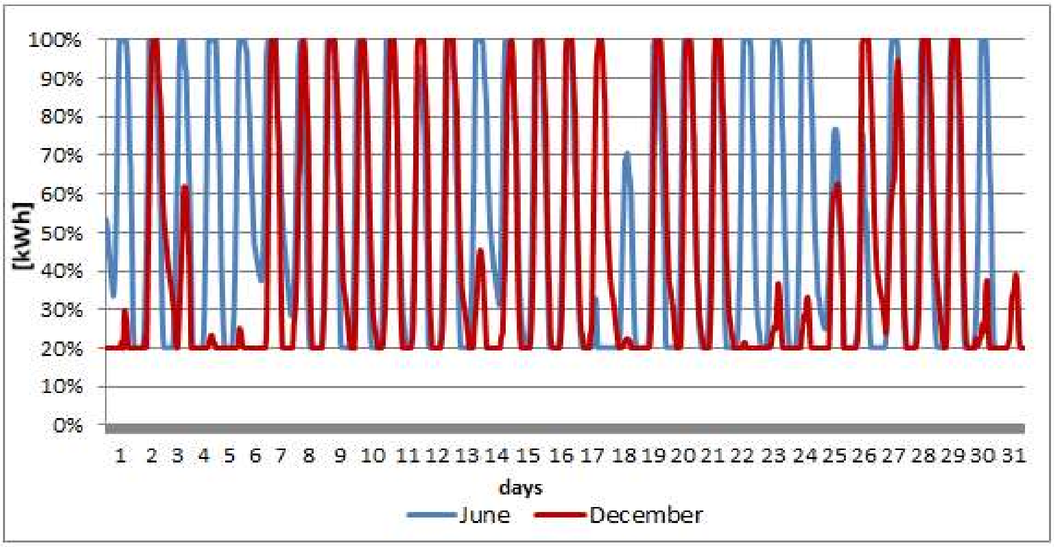

Figure 14. Battery state of charge in June and December (case 2)

3.4 Case 3 (Stand Alone)

The electric scheme of the system is reported in Figure 15. The main difference compared to the previous types consists in the fact that the load is uniquely satisfied by the system, so that the battery is sized in order to contain all the necessary energy reserve: it therefore results in the need to upgrade the PV system. Nevertheless, the storage capacity does not contain all the excess energy, not self-consumed, very high in summer months, that will be consequently lost, being present no other devices to be powered.

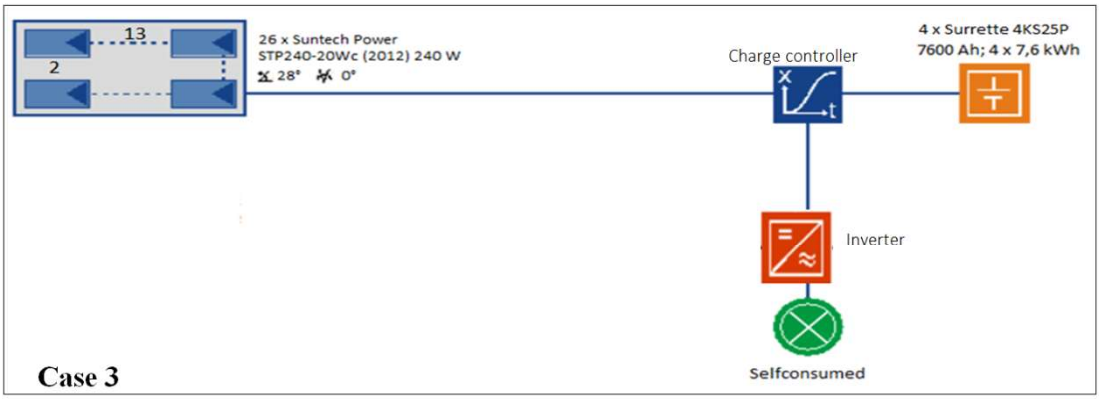

Figure 15. Electrical scheme of the plant for case 3

A possible and interesting use of energy surplus (not considered in the present study) would be the partial satisfaction of thermal energy demand, in the study guaranteed through a methane boiler, that could be consequently assisted by the electric system.

The sizing of the generator has been determined in order to satisfy the load even in the worst case, corresponding to the day of maximum winter consumption, also in the eventuality of PV minimal production. It was consequently determined as ratio between the daily maximum winter consumption (occurred on December 18st, equal to 8.2 kWh) and the daily minimum winter equivalent hours (on December 21nd, equal to 1.32 h), corresponding to 6.2 kW_p. Adopting a module with a power of 240 W, 26 modules must be used.

Energy production can be seen in Figure 16: as expected, it is markedly greater than the load to satisfy. The sizing of the battery has been carried out in order to guarantee the maximum daily load for 3 days (8.2 kWh x 3 = 24.6 kWh): adopting the same batteries as in case 2 (capacity = 7.6 kWh), four of them are required, for a total storage capacity of 30.4 kWh. A simulation aimed at monthly determining the minimum reached charge verification was carried out in the colder months, in which the battery capacity, and therefore its state of charge, is more reduced.

Table 3 reports the load and the energy rates (inverter output, self-consumed, stored or taken from the battery). It is:

Energy production = Self-consumed energy + battery income + energy surplus

Load = Self-consumed energy + battery withdrawal

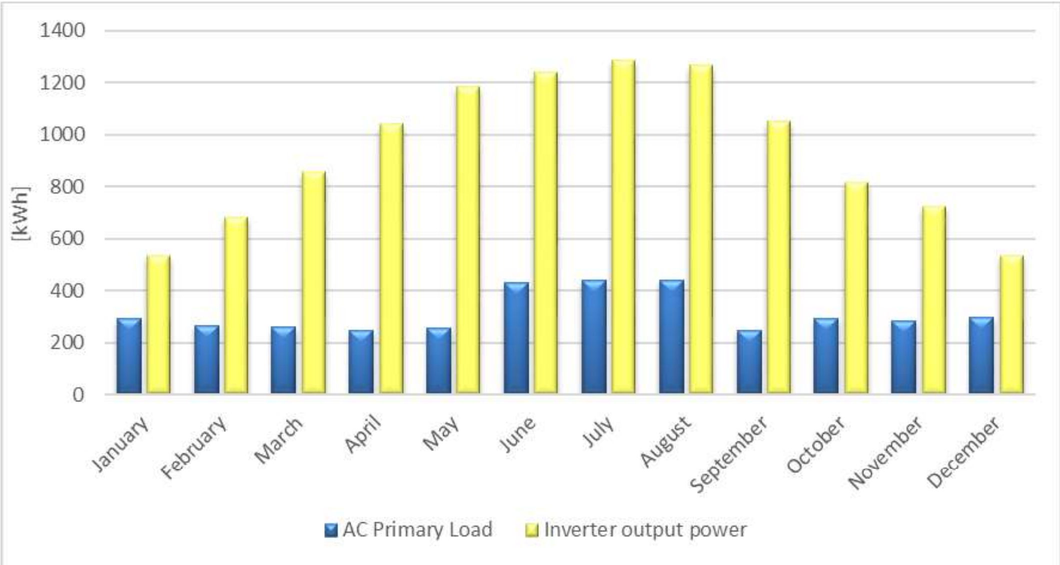

Figure 16. Monthly load and PV production (case 3)

Table 3. PV plant energy rates (case 3)

Yearly Energy (kWh)	
Load	3,942
Inverter output	11,204
Self-consumed energy	1,522
Battery withdrawal	2,420
Surplus energy	7,262

In Figures 17 and 18 respectively the load rates and the production ones are reported.

Figure 19 shows the state of charge of the batteries in June and December. As we can see, in the latter month the battery state presents deep discharge cycles, lasting 3-4 days (days 14-18 and 20-24); the behavior is different in June, in which fairly regular daily oscillations are present: during the day the battery recharges, and discharges maximum 30% at night. It can also be noted that, due to the abundant photovoltaic production, the battery is often completely charged, deeply discharging only in two cases, but never beyond 65%.

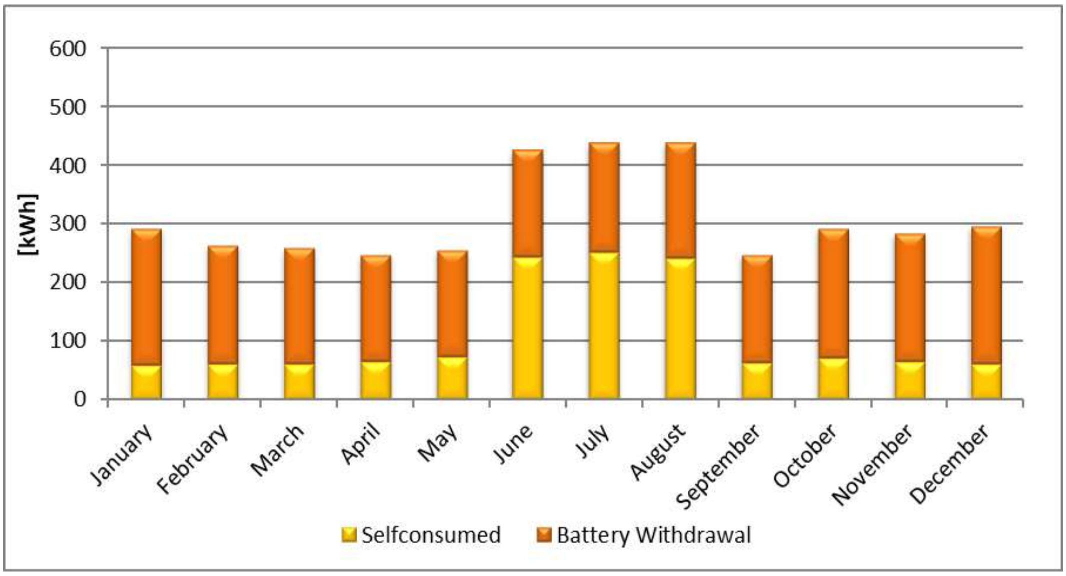

Figure 17. Self-consumed PV production and battery withdrawal (case 3)

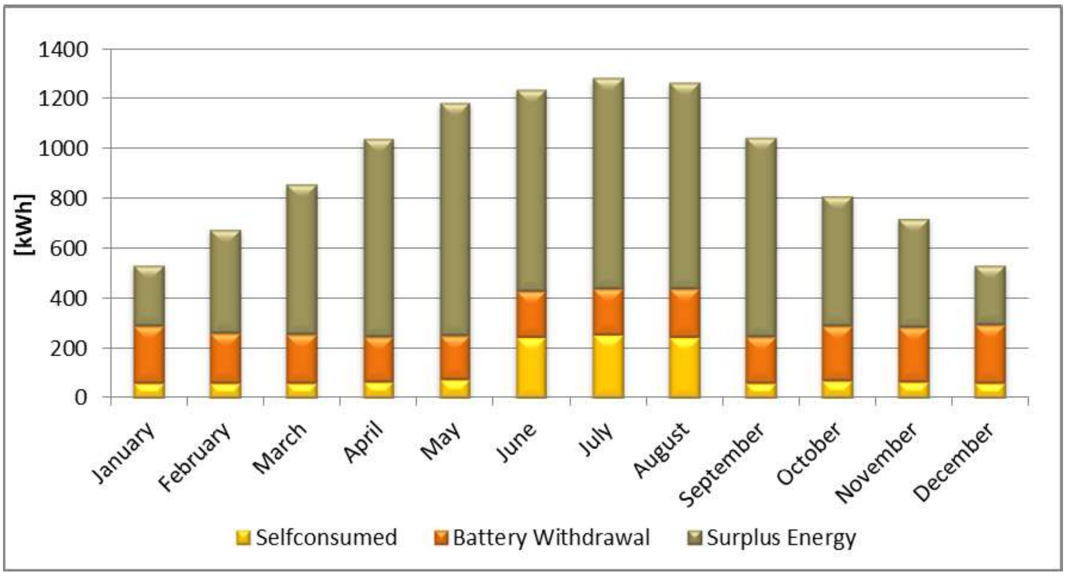

Figure 18. Self-consumed PV production, battery income and energy exported to the grid (case 3)

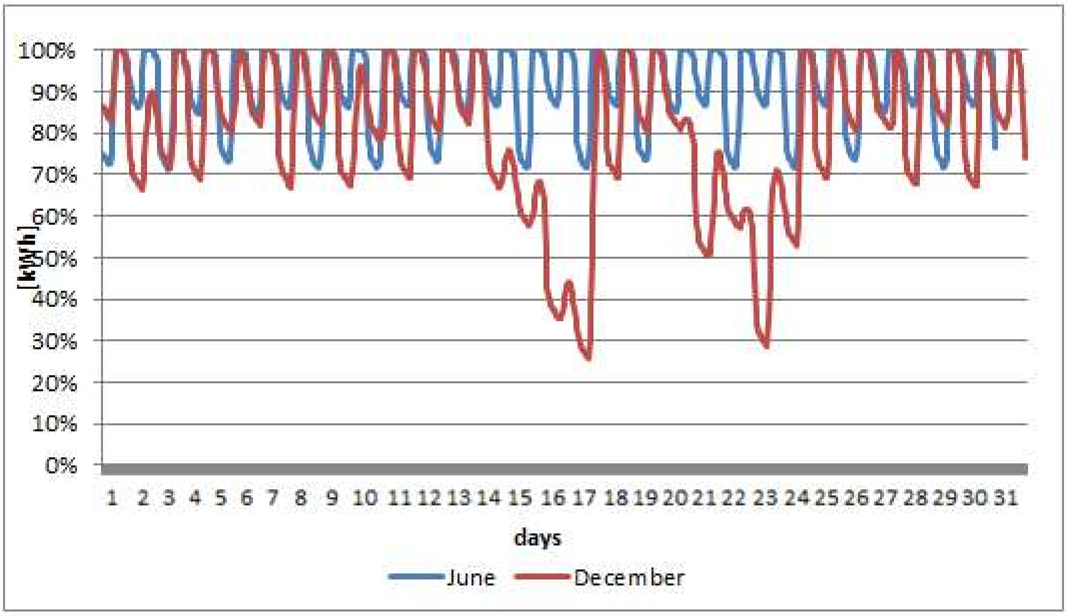

Figure 19. Battery state of charge in June and December (case 3)

3.5 Case 4 (Smart)

A very basic smart system was analysed, connecting the residential user so far considered (LOAD 1, as reported in Fig.5), satisfied by a 3 kW_p plant, to a second one (LOAD 2), a commercial activity with a mostly diurnal complementary load, satisfied by a 2 kW_p system (Figure 20).

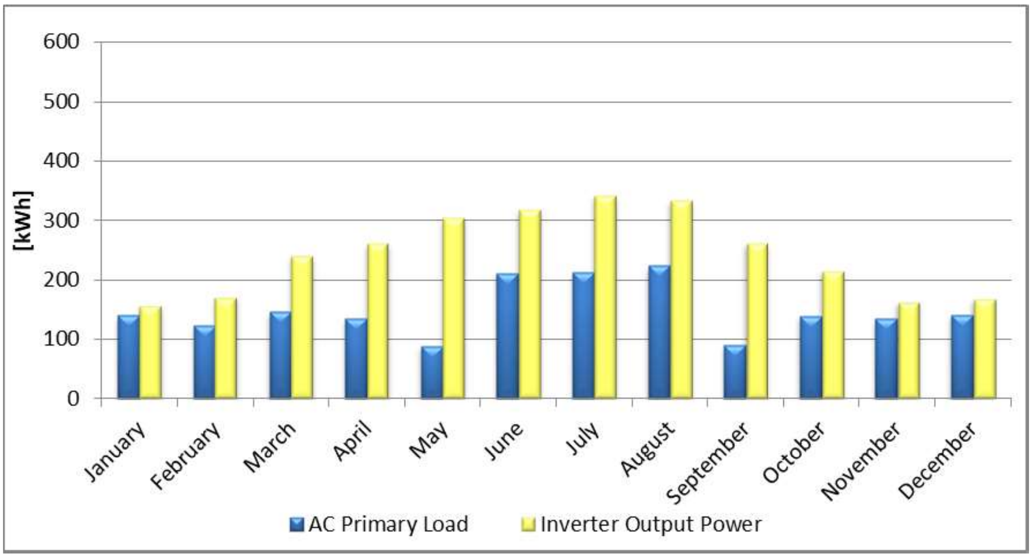

Figure 20. PV production and load of user 2 (LOAD 2)

Both users are served by a same system, a smart plant with total power equal to the sum of the individual ones, 5 kW_p, serving a total load equal to the sum of the individual loads and managing energy production in an intelligent way, reciprocally exchanging between the users, before sending to the grid, the respective production redundancies.

The electric scheme of the system is reported in Figure 22. The case of the smart plant (Fig.21a) has been simulated through Excel data sheet and compared to that of two loads satisfied by two separate plants (Fig.21b), analysed using PVSol.

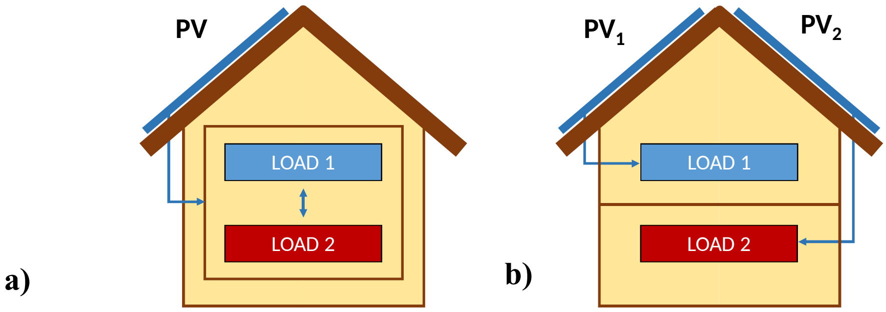

Figure 21. *Smart* system for two users (left) or each user served by his own system (right)

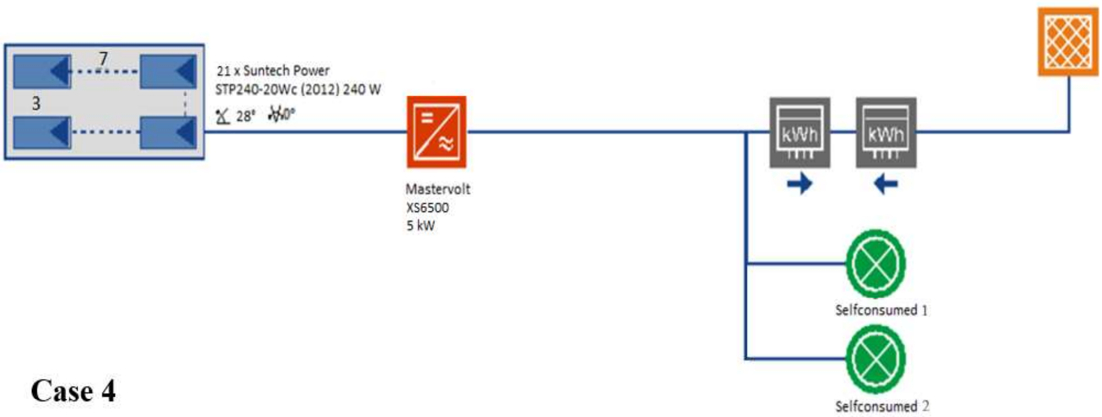

Figure 22. Electrical scheme of the plant for case 4

Table 4 reports the energy rates for the two configurations (inverter output, self-consumed by each user, fed into the grid – sales - and withdrawn from it – purchases -), Figure 23 shows the energy rates withdrawn and exported to the grid by the smart system and the corresponding fluxes for the two separate plants: it can be seen that exchanges with the grid are reduced for the smart plant, being 541 kWh of crossed flows exploited before being sent to the network and withdrawal are reduced of 335 kWh.

Table 4. Load and PV plants energy rates (case 4)

Yearly Energy (kWh)			
	Smart Plant	*PV1 + PV2*	
		PV1	*PV2*
Load	5,723	3,942	1,781
Inverter output	7,315	4,389	2,926
Self-consumed energy	2,779	1,364	874
Grid sales	4,536	3,025	2,052
Grid purchases	3,150	2,578	907

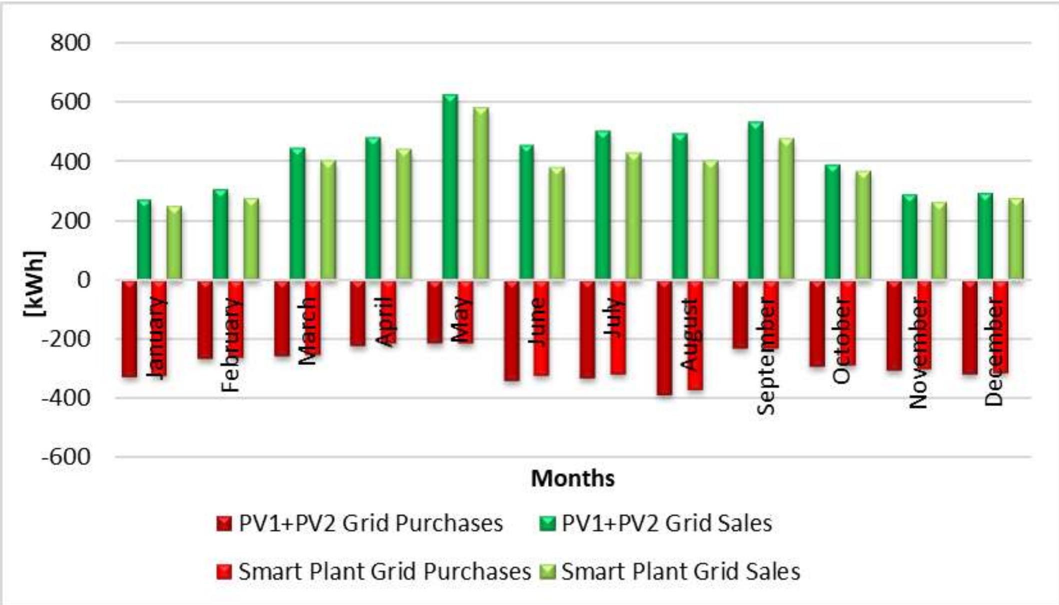

Figure 23. Incoming and outgoing energy flows in the case of smart plant

4. ECONOMIC ANALYSIS

The economic comparison of the PV plant configurations has been made by calculating the *Net Present Cost* (*NPC*):

$$NPC\ (€) = \sum_{i=0}^{N} \frac{C_i - B_i}{(1+r)^i} + I \tag{1}$$

in which:

i year
N number of years
C costs
B benefits
I investment cost
r rate of discount.

The indicator provides information on costs incurred during the 25-year life of the plant.
The supported costs are the investment and the functioning ones, these latter referred to the price of energy withdrawal, whereas the benefits are the sum of the income tax deduction, corresponding to 50% of the investment cost, distributed in ten years, and the incentive provided by the *on site exchange* mechanism (Table 5) which balances economic values

of energy exchanged with the grid and remunerates exceeding production sent to the grid. Energy taken from the grid is paid with an omni comprehensive price (0.22 €/kWh) while energy injected to the grid is sold considering different contributes: the energy one, paid at 0.08 €/kWh, the grid services, at 0.06 €/kWh, and exceeding energy, at 0.08 €/kWh. The discount rate was assumed equal to 1%.

Table 5. Net Present Cost of the analysed configurations.

Type	PV Power (kW_p)	Investment cost (€)	Functioning Cost (€/y)	Income tax deduction (€/y)*	On site exchange (€/y)	Total benefits (€/y)	NPC (€)
Grid connection (no PV system)	3	-	737	-	-	-	16,033
Grid Connected PV System	3	6,000	484	300	367	667	5,119
Storage on Grid PV System	3	6,500 (+500 €/5 years)	156	325	164	489	8,252
Stand Alone PV System	6.2	14,500 € (+2,000 €/5 years)	-	750	-	750	14,972
Smart PV Systems	5	10,000	635	500	590	1,090	6,260
PV1 + PV2	5	10,000	654	500	565	1,065	7,233

*for the first ten years

4.1 Case 0 (grid connection - no PV system)

Being present no investment costs or benefits, NPC is valued only as a function of the operating cost for the 25 years of plant life. Using an average all-inclusive energy price equal to 0.187 €/kWh, the total cost needed to meet yearly electricity demand (3,942 kWh) is € 731. For this case, the highest NPC among configurations is observed (€ 16,033).

4.2 Case 1 (Grid Connected)

In such case the terms determining NPC are both investment (including inverter restore, every ten years, in all configurations) and operating costs, and benefits deriving from the on-site exchange mechanism and income tax deduction. The previously introduced unit cost of energy has been used. It is observed that NPC is strongly lower (€ 5,119) than that relating to the previous case.

4.3 Case 2 (Storage on Grid)

Being a hybrid system, in the investment cost also the batteries one (€ 500/each) is present; moreover, since their lifespan is approximately 5 years, it is necessary to consider their restoration every 5 years. The PV plant cost is equal to that of the previous case, since the power of the generator has not changed. As it is evident, NPC values (€ 8,252) are higher than the previous case, due to the presence of the battery acting as a buffer with the network.

4.4 Case 3 (Stand Alone)

In the calculation of NPC, the investment cost is greater than the previous cases, for both the greater power of the system and the presence of batteries. In this case there are neither costs deriving from energy withdrawing nor benefits due to the introduction of energy into the network; the only contribution to the benefits is that deriving from income tax deduction. NPC values are high (€ 14,972), close to those of grid connection with no PV system, so at the moment, in absence of further incentives, the installation of this type of system is not very convenient.

4.5 Case 4 (Smart)

From Table 1 it can be observed that the smart system results more convenient than the (3+2) kW_p separate plants, allowing saving 973 € in the plant life compared to the case of two separate plants.

4.6 Systems comparison

Figure 24 shows NPC values obtained for the analyzed cases. The most convenient configuration results the grid connected system, since it allows, at the end of the 25 years of operation of the system, to save 10,914 € compared to the most unfavorable case, that of network connection without PV system. The stand-alone system is also relatively expensive, due to the high investment cost, while storage on grid has intermediate costs.

Referring to case 4, comparing the sum of the two distinct PV plants and their smart management, the intelligent configuration results more convenient, saving at the end of 25 years plant life € 973.

For the best case the optimal PV power which allows to minimize NPC has also been calculated, determining the respective values for PV powers varying from 3 to 12 kW_p: a higher power than that used has been obtained, equal to 6 kW_p (Figure 25).

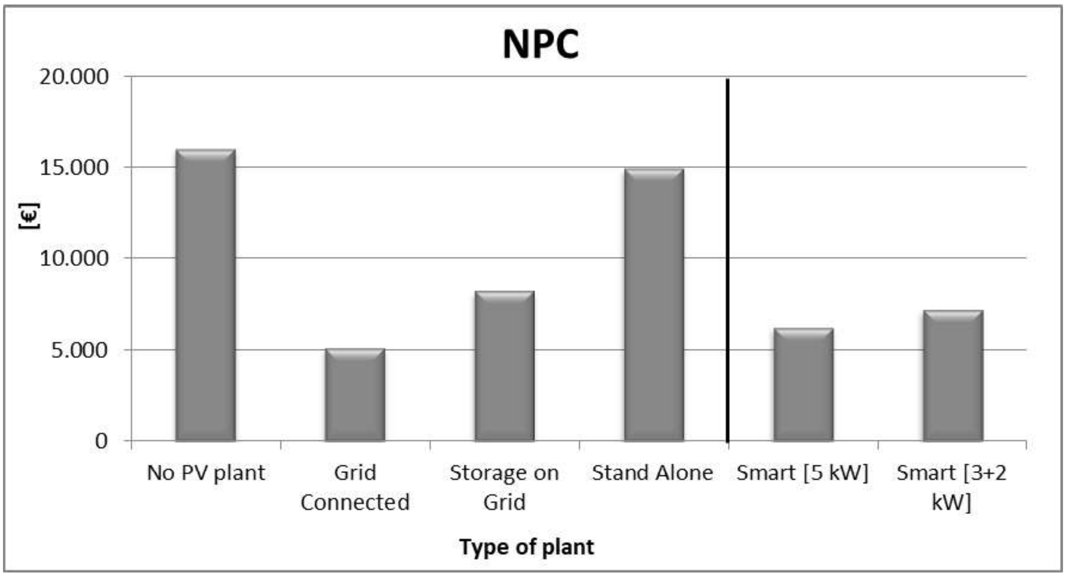

Figure 24. Comparison among NPCs in the analysed cases

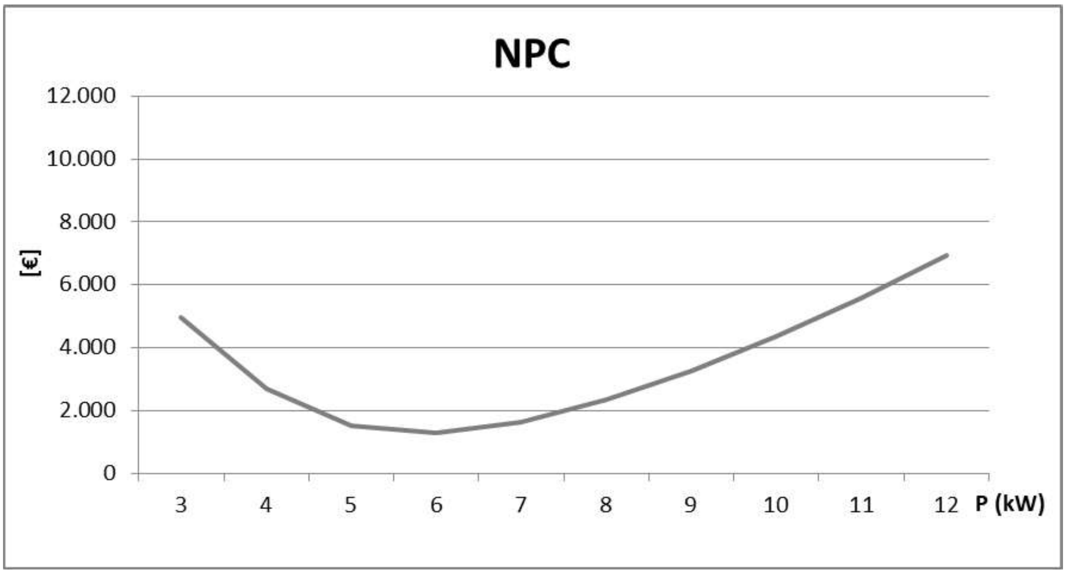

Figure 25. NPC trend vs. PV plant power

5. PRIMARY ENERGY BALANCES

In order to assess the primary energy balances, the yearly primary rates of both electric energies exchanged with the grid and thermal energy obtained from methane combustion have been calculated. It is [58]:

$$E_p = \sum_k E_{p,del,k} - \sum_k E_{p,exp,k} = \sum_k (E_{del,k} \times f_{p,del,k}) - \sum_k (E_{exp,k} \times f_{p,exp,k}) \quad (2)$$

where:

E_p primary energy [kWh/year]

k	energy vector
$E_{p,del}$	primary energy delivered to the user [kWh/year]
$E_{p,exp}$	exported primary energy [kWh/year]
E_{del}	energy delivered to the user [kWh/year]
E_{exp}	exported energy [kWh/year]
$f_{p,del}$	primary conversion factor of energy delivered to the user [-]
$f_{p,exp}$	primary conversion factor of exported energy [-] [59].

The primary conversion factor for energy delivered to the user, $f_{p,del}$ is equal to 1.05 for thermal energy and 1.95 for electric energy; the conversion factor $f_{p,exp}$ for energy exported, present only for electric energy, is equal to 1.

5.1 Thermal energy

Thermal energy required to meet the load (9,209 kWh/year), obtained through methane combustion, converted into primary energy corresponds to an amount of 9,669 kWh/year.

5.2 Electric energy

The rates of electricity yearly exchanged with the grid have been calculated in terms of primary energy. Table 6 reports, for each configuration, the energy rates delivered and exported and the same aliquots converted into primary energy, together with the primary energy balances; a graphical comparison among the balances is shown in Figure 26.

The stand-alone configuration obviously shows a nil balance, since electricity production is entirely renewable; low values are shown by all the PV configurations, both with and without storage, which are markedly lower than the budget for the exclusive supply via the electricity grid, of fossil origin, resulting particularly high (7,687 kWh).

The comparison between the smart system and the two separate plants shows that the former, exploiting users' reciprocal redundancies, has a reduced delivery of 335 kWh and allows saving 113 kWh in the primary energy balance.

Table 6. Primary energy balance for the various configurations, referred to electric energy

Type of system	Energy (kWh)		Primary Energy (kWh)		
	E_{del}	E_{exp}	$E_{p,del}$	$E_{p,exp}$	E_p
Grid connection (no PV)	3,942	-	7,687	-	7,687
Grid Connected PV	2,578	3,025	5,027	3,025	2,002
Storage on Grid PV	1,629	833	3,177	833	2,344
Stand Alone PV	-	-	-	-	-
Smart PV	3,150	4,536	6,142	4,536	1,606
PV1+ PV2	3,485	5,077	6,796	5,077	1,719

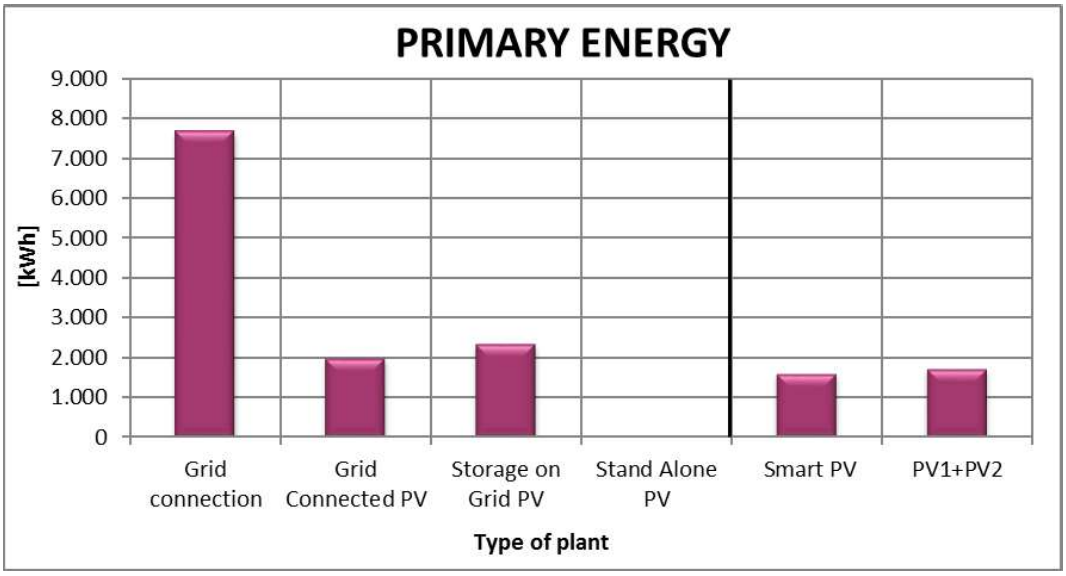

Figure 26. Balance of primary energy in relation to the rates of electricity

5.3 Primary energy balances

Table 7 shows the results of the total primary energy assessments for the various configurations, including both thermal and electric energy, and Figure 27 shows a comparison among the primary energy balances. They provide significantly higher values due to the presence of the fossil methane source, being the corresponding term very high (9,669 kWh): the replacement of the boiler with an electrically driven system could drastically reduce energy delivered.

Table 7. Primary energy balances

Type of system	Primary Energy (kWh)		
	$E_{p,del}$	$E_{p,exp}$	E_p
Grid connection (no PV) + Boiler	17,356	-	17,356
Grid Connected PV + Boiler	14,696	3,025	11,671
Storage on Grid PV + Boiler	12,846	833	12,013
Stand Alone PV + Boiler	9,669	-	9,669
Smart PV + Boiler	15,811	4,536	11,275
PV1+ PV2 + Boiler	16,465	5,077	11,388

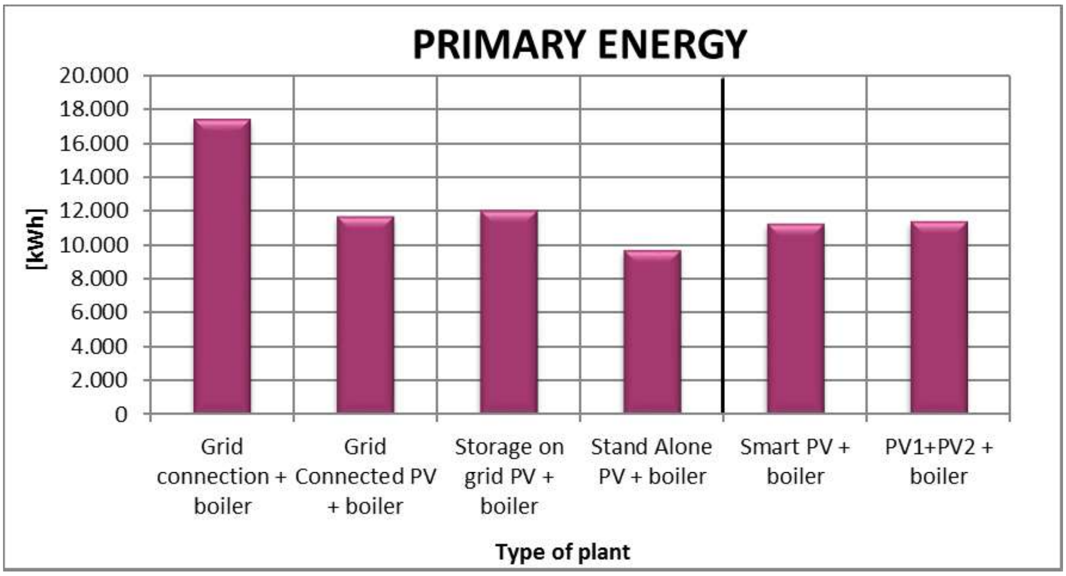

Figure 27. Balance of primary energy in relation to the rates of both electric and thermal energy

6. CO_2 EMISSIONS

Starting from the values of energy delivered, the total CO_2 emissions produced by the various configurations have been calculated using emission factors referring to both electrical and thermal consumption. Particularly a value of 0.46 kgCO_2/kWh has been adopted for the emissions ascribable to electric consumption and a value of 0.202 kgCO_2/kWh for those linked to the thermal one. The results are reported in Table 8 and Figure 28.

Table 8. Total CO_2 emissions for the different cases

Type of system	CO_2 emissions (kg/year)		
	Electric	Gas	Total
Grid connection (no PV system) + Boiler	1,813	1,860	3,674
Grid Connected + Boiler	1,186	1,860	3,046
Storage on Grid + Boiler	749	1,860	2,609
Stand Alone + Boiler	-	1,860	1,860
Smart PV system + Boiler	1,449	1,860	3,309
PV system (3+2) kW + Boiler	1,603	1,860	3,463

Since emissions due to thermal consumptions are constant for all configurations (1,860 kgCO_2/year), the one composed by boiler plus stand-alone system shows the lowest emissions, coinciding with those related to the thermal production, being nil those due to the electrical production by RES. On the contrary, the satisfaction of electricity consumption by drawing energy from the grid, responsible of 1,813 kgCO_2/year, corresponds to the emission peak. As regards the comparison between the two users managed in a smart way or as sum of plants, the former mode allows saving 154 kg CO_2/year.

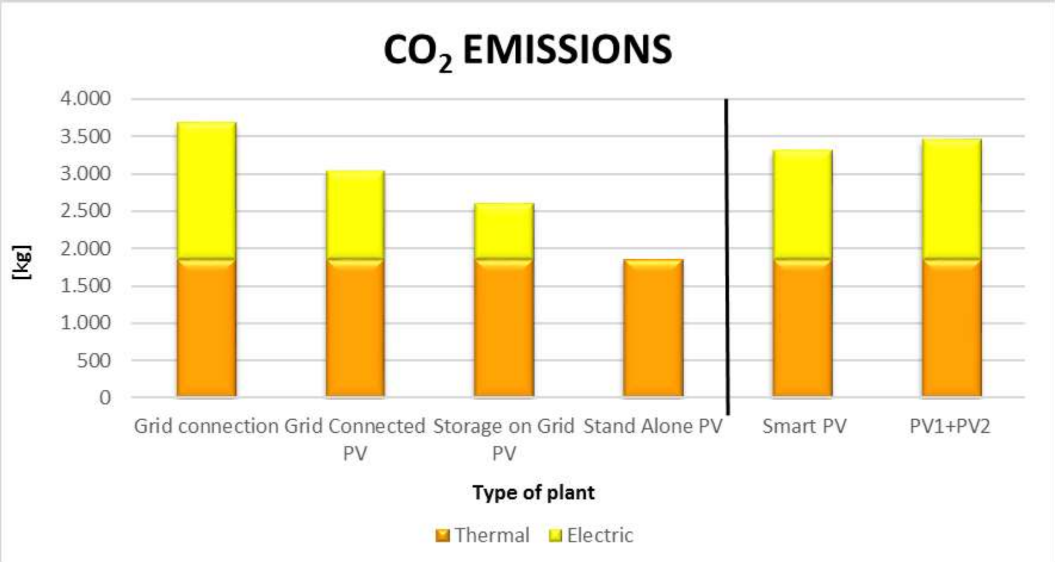

Figure 28. Total CO_2 emissions referring to both thermal and electric consumption

7. CONCLUSIONS

In this work, with reference to a case study, consumption reduction interventions aimed at meeting the electrical requirements of a residential user located in Reggio Calabria (Southern Italy) through renewable sources have been applied. User's energy needs have been analyzed, the thermal requirements of which are met through a methane boiler, while the electrical ones are guaranteed through a connection to the electric grid.

In order to reduce the use of conventional energy sources in favor of solar energy, a PV system declined in different configurations (grid connected, storage on grid and stand-alone) has been analysed to satisfy electrical demand. In addition, the case of a very basic smart system was considered, in which the user is connected to a second one and both exploit the production of the same plant, with power equal to the total separated utilities, reciprocally exchanging between the users, before sending to the grid, the respective production redundancies.

The irradiation and the loads have been simulated through the *PV Sol* software, whereas energy production and rates through *HOMER*. The systems have been evaluated from an economic point of view calculating the *Net Present Cost* at the end of 25-years plants life.

Yearly primary energy balances with reference to both electricity and heat supply have been assessed for all the configurations. As concerns the environmental aspect, the produced CO_2 emissions associated to each energy type have been calculated starting from the respective delivered energy values.

From an economic point of view, among all the considered configurations, the most convenient type resulted the grid connected PV plant, which allows saving € 10,914 at the end of plant life with respect to the most expensive case, that of network connection without PV. The stand-alone configuration resulted the least convenient among the PV plants (€ 14,972), due to the high cost supported for the plant over-dimensioning and storage, whereas the smart plant allows saving 973 € with respect to the sum of separate plants.

As concerns primary energy balances, referring to electrical energy, the plant providing the lowest value was obviously the stand-alone one, due to the absence of electricity drawn from the grid, in relation to which needs it results in a nil balance. Low values are shown by all the PV configurations, both with and without storage, markedly lower than those due to the exclusive supply via the electricity grid, of fossil origin, particularly high (7,687 kWh). The comparison between the smart system and the separate plants shows that the former, exploiting users' reciprocal redundancies, has a reduced delivery of 335 kWh and allows saving 113 kWh in the primary energy balance.

The primary energy balances considering both energy sources (electrical and thermal) provide significantly higher values due to the presence of the fossil methane source, being the corresponding term very high (9,669 kWh): the replacement of the boiler with an electrically driven system could drastically reduce energy delivered.

Concerning CO_2 emissions, since their value is due to both thermal consumption, constant for all configurations (1,860 $kgCO_2$/year), and electrical one, obviously the configuration formed by the boiler plus the stand-alone PV system, which does not generate emissions for electricity production, shows the lowest total emissions, coinciding with those related to thermal production. The peak emissions are ascribable to the satisfaction of electricity consumption through exclusive withdrawal from the network (1,813 $kgCO_2$/year). Finally, the use of an intelligent system, reducing energy withdrawal, generates fewer CO_2 amounts compared to the case of two separate plants serving the respective loads (154 kg CO_2/year saved).

Concerning photovoltaic systems in conclusion it can be stated that at the moment stand alone ones, although convenient from an environmental point of view, still point out remarkable critical issues concerning both cost and excess energy storage in summer seasons, so that, independently on the locality, grid connected configurations, both with and without storage, presently result the most recommended ones. Further development of grid connected systems, showing additional benefits, will be PV systems endowed with smart supply management of more users, connected among them and with the grid, in such a way to exploit reciprocal PV production redundancies before sending them to the grid.

NOMENCLATURE

B	benefits [€]
C	costs [€]
E_p	primary energy [kWh/year]
$E_{p,del}$	primary energy delivered to the user [kWh/year]
$E_{p,exp}$	exported primary energy [kWh/year]
E_{del}	energy delivered to the user [kWh/year]
E_{exp}	exported energy [kWh/year]
$f_{p,del}$	primary conversion factor of energy delivered to the user [-]
$f_{p,exp}$	primary conversion factor of energy exported [-]
i	year [-]
I	investment cost [€]
k	energy vector
N	number of years [-]
NPC	Net present cost [€]
r	discount rate [%]

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