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PV Self-Consumption and Self-Sufficiency for Household and Office Users: The Lockdown Effects During the COVID-19 Pandemic

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ABSTRACT

The lockdown period due to the COVID-19 pandemic and the consequent adoption of homeworking had effects also on the energy sector, by shifting electrical consumption from tertiary to residential sector. This article analyzes the electric load curves in the office and at home for a group of employees, estimating the change of the Self-Consumption (SC) and the Self-Sufficiency (SS) when PV plants are installed, during the two months of the lockdown period (2020) with respect to the previous year. This investigation can help to explore the impact of homeworking, which is now usually adopted by many employees. For this purpose, the impact of different PV sizes on SC and SS rates, and the improvements due to the adoption of Battery Energy Storage Systems (BESS), are analyzed. Sizing the PV production equal to the annual consumption and the BESS capacity equal to the difference between the average PV production and the average consumption, the annual SC (=SS in this case) increases from 35% to 68% in households and from 50% to 71% in the office building. The lockdown restrictions increase and decrease these rates of about 5-7 points in households and office building respectively.

1. INTRODUCTION

Working from home has got increased since the beginning of COVID-19 pandemic. Besides social aspects, the use of home working impacts also on the energy sector (final energy consumption) and on the environment (GHG emissions). For a comprehensive analysis of these consequences, changes in commuting consumption, in heating and in electric uses, in both homes and offices, are to be evaluated. Monitoring real data remains essential, since actual community behaviors are difficult to be foreseen.

In this work some data, concerning electric consumption, are collected for households and offices during the Italian lockdown period (March-May 2020), which might portrays an extreme application of home working.

Consumption data for residential users during the lockdown period are collected also for example in Ref. [1] in Poland, where an average of 16% of increased consumption has been observed, with respect to previous years. A good literature review on energy consumption variation during COVID-19 periods can be found there.

Apart from the effects on GHG emissions and local pollution, working from home shifts, during daylight hours, the power profile demand from offices to home and this impacts also on PV benefits, whenever PV plants are installed.

Our previous paper [2] investigated this aspect on a sample of 10 households: the amount of daily electric energy consumption that has been shifted from the offices to home, is estimated to be about 1-1.2 kWh/day/person. This shift affects the amount of energy exchanged with the electric grid, and therefore, if PV plants are installed, the Self-Consumption rate (SC), i.e. the ratio of absolute self-consumption to PV production, and the Self-Sufficiency rate (SS), i.e. the ratio of absolute self-consumption to user consumption. High values of SC and SS rates guarantee, respectively, lower injection and demand from the electric grid. Thus, not only the grid stress is minimized, but also the dependency from the external grid is decreased. A broader discussion of the definitions of SC and SS can be found in Ref. [3].

As an example of consequence of the lockdown period, in the cases analyzed, SC at home raised from 32% to 50%, while SS remained steady at the 40-42% level (because both numerator and denominator increased) [2].

Furthermore, this shift influences also the financial aspects (net present value, payback period, internal rate of return, etc.) even if the economic features are not included in this study.

In Italy, almost 1 million PV plants turn out to be installed (at the end of 2020), corresponding to a rated power of 21.7 GW. The average Italian figures of self-consumptions and self-sufficiencies (for the plants having actual self-consumption) are: 35% SC for residential (SS rate=30%), 50% SC in tertiary sector (SS=17%), 58% SC in industry, 40% SC in agriculture (data in 2020 [4]).

The rates of SC and SS can be increased thanks to the use of Battery Energy Storage Systems (BESS), whose costs have been reduced during the last years. A reduction down to about 1000 euro/kWh (kWh of capacity) in 2019 has been reported for example in Ref. [5]. Even if the adoption of BESS still remains limited, because of economic reasons, their choice is expected to become more and more attractive, if costs keep decreasing in an important way.

At the end of 2020, in Italy, almost 40,000 installed storage systems (connected to PV plants) are registered. Since 2015, the rate of installation of storage system has been increasing remarkably, especially in 2020, when it raised sharply by 50% compared to the previous year [4].

In recent years, many papers about PV and BESS sizing in residential environment have been published. A good overview and discussion of this increasing number of publications can be found in Ref. [6]: different key parameters of optimal planning are listed there and the need of practical guidelines for customers is there underlined.

The novelty of this paper content is the focus on home working (lockdown period) and on the comparison between residential and office environments. Real data are monitored and collected for 10 families, and for an office building, including the activity of 75 employees, whereas the PV production and the electricity storage are simulated by a software. The data cover a period of 1-2 years (2019-2020).

More specifically, the objectives of this study are:

- exploring the influence of electric consumption, home working, rated power of the PV systems in the office and at home on SC and on SS rates;
- exploring the impact of the BESS on SC and SS at home and in the office.

The results are generalized as much as possible, showing the simultaneous dependency of the different variables, in order to obtain a comprehensive view of the different effects (e.g. change of the residential load profile).

In this paper, only the electric energy is examined, while the inclusion of energy consumption for transport and heating is expected to be object of future works.

2. METHODS

2.1 Self-Consumption and Self-Sufficiency definitions

Simulation calculations are performed by means of functions developed in the OCTAVE software (https://www.gnu.org/software/octave/about), both for the PV production and for the impact of the adoption of BESS. As common approach, when the PV production curve is higher than the load curve values (active power), the excess energy is stored in the BESS. When the BESS capacity is fully charged, the power is switched towards the electric grid. On the other side, when the load curve is higher than the PV production, the missing energy is taken from the BESS or, if completely discharged, from the electric grid. In this simulation no limit is foreseen on the power injected into the grid, or withdrawn from the grid, since this limit depends on specific applications and country laws.

Therefore, the PV absolute self-consumption, without BESS, is obtained integrating A(t) (kW), that is formally defined as:

$$A(t) = \min\{L(t), P_{gen}(t)\}$$

where, $L(t)$ is the instantaneous user active power load and $P_{gen}(t)$ is the instantaneous onsite PV power generation. In case of adoption of BESS.

$$A(t) = \min\{L(t), P_{gen}(t) - P_{diff}(t)\}$$

where, $P_{diff}(t)$ is the power to and from the storage unit, with $P_{diff}(t) > 0$ when charging and $P_{diff}(t) < 0$ when discharging [3].

The self-consumption rate (*SC*) is the ratio between absolute self-consumption and the power generation, whereas the self-sufficiency rate (*SS*) is the ratio between absolute self-consumption and the user consumption:

$$SC = \frac{\int_{t=t_1}^{t_2} A(t)dt}{\int_{t=t_1}^{t_2} P_{gen}(t)dt}$$

$$SS = \frac{\int_{t=t_1}^{t_2} A(t)dt}{\int_{t=t_1}^{t_2} L(t)dt}$$

In this study, SS and SC rates have been calculated with a time step of 1 hour and $(t_2 - t_1)$ refers to the considered time period, e.g. 1 year (y).

Their variation is shown in section 3 for different rated power of the PV plants installed, the variable being expressed as annual PV production (kWh/y) divided by the annual consumption (kWh/y). As a matter of fact, the SC and SS rates are independent of the ratio thus defined (production/consumption), as long as the shape of the load profile remains unchanged (e.g. a house with 1.6 kWp and consumption of 2,100 kWh/y has the same SC and SS rates as a house with 3.2 kWp and consumption of 4,200 kWh/y).

Moreover, in order to investigate the SC and SS dependencies on the BESS capacity C_{bat}, the ratio between the C_{bat} (in kWh) and the annual consumption (MWh/y) is chosen as independent variable. As a matter of fact, when no limits are imposed for $P_{diff}(t)$, the SC and SS rates have the same results for [$L(t)$, $P_{gen}(t)$, C_{bat}] as for [k$L(t)$, k$P_{gen}(t)$, kC_{bat}]. Therefore, the cases [$L(t)$, $k_1 \cdot P_{gen}(t)$, $k_2 \cdot C_{bat}$] can be representative of all the cases.

The output diagrams obtained in this way (see Section 3) can thus characterize and generalize the results for SC and SS rates, as long as the consumption shape is fixed, together with the features and performances of the PV installed (e.g. location, tilt, orientation, efficiency, etc.). The resulting curves do not depend on the annual consumption (kWh/y) and the kWp size, but only on their ratio.

In this way, the dependency of SC rate on PV rated power (normalized to consumption) and on the BESS capacity (again normalized to consumption) can be shown in a single graph by 3D diagrams (see Section 3.1) (as long as the shape and PV panel performances do not change).

2.2 Photovoltaic plant model description

The PV production simulation is obtained, hour by hour, following the method of [7], according to actual solar radiation data of 2019 [8], assuming crystalline silicon cells and system losses of 10%.

The power production is estimated by the decomposition of solar radiation on horizontal and inclined plane, with different orientation, and by the rated power of PV modules, according to the relationship [7]:

$$P_{gen} = P_{stc} \frac{I_t}{G_{stc}} \eta_{rel}(I_t, T_m)$$

where, P_{gen} is the power generation in real conditions (kW),

P_{stc} is the rated power of the PV plant, G_{stc} = 1000 W/m^2 is the conventional radiation in Standard Test Conditions (STC) and $\eta_{rel}(I_t, T_m)$ is the relative efficiency, that is function of the global solar radiation I_t, captured by the PV plan, and the PV module operating temperature T_m.

The location of the PV panels is assumed to be in Bologna (Italy), with 30° of tilt, 0° south direction. The annual energy production per rated power, with these assumptions, turns out to be 1265 kWh/kW$_p$ in our simulations. In Italy the ratio kWh/kWp of real PV panels lies mostly in the range 900-1500 kWh/kWp, with a value of 1122 (in 2019) in Emilia Romagna (the region of Bologna) [4].

The simulation model, implemented in OCTAVE, has been validated using the European PVGIS web application [9] within an average error of 3%.

The study does not take into account the PV surface availability on the roofs/ground, since this is case dependent whereas the focus here is on the general SC dependency.

2.3 Electrical storage model description

The behavior of the BESS has been modelled with the following assumptions. The simulation concerns any type of batteries because a simplified model was used here. According to Ciocia et al. [10], and applying the same efficiencies values in charge and discharge phase, the state of charge (*SOC*) of the battery is calculated by the following equations:

$$SOC(t_i) = SOC(t_{i-1}) + \frac{P_{bat} \cdot \Delta t}{C_{bat}}$$

$$P_{bat} = \eta_{bat} \cdot \eta_{inv} \cdot P_{diff} \quad \text{if} \qquad P_{diff} > 0$$

$$P_{bat} = \frac{P_{diff}}{\eta_{bat} \cdot \eta_{inv}} \quad \text{if} \qquad P_{diff} < 0$$

where, P_{diff} is the excess power, when greater than zero (due to the difference between PV production and load) and the required power, when less than zero. η_{bat} and η_{inv} are, respectively, the battery efficiency and the inverter efficiency, both assumed to be constant to the value of 0.95 and 0.94 [11]. C_{bat} is the net (or usable) capacity of the battery in order to avoid to consider the real maximum level of charge. Therefore, *SOC* can be used in the range between 0% and 100%.

The battery charge and discharge power, normalized to the usable battery capacity, is assumed to be limited to 1 kW/kWh, as in Ref. [11]. The BESS capacity is sized in such a way to be equal to the difference between the PV production and the self-consumption. This is calculated from the difference of the integral between the average production and the average load curves, by considering an annual average behavior.

3. SIZING OF PRODUCTION AND STORAGE

3.1 Sizing for office buildings

Electric consumption at offices has been investigated by considering a building attended by employees using typical office equipment, with R&D and administrative tasks (in Bologna, Italy). Consumption is not monitored individually, but for the whole building, hosting, in about 70 rooms and 1600 m^2, about 100 employees (with an average of 75 employees actually present daily).

The monitored data are collected in a quarter-hour electrical load curve in the years 2018-2020. The annual electricity consumption for the building turned out to be 52,268 kWh/year and this corresponds to the energy produced annually by a simulated PV panel of about 42 kW$_p$. More information can be found in Ref. [2], where also the active power load per employee has been estimated thanks to a monitoring system of the building employee occupancy.

The average behavior of the load curve during the day, of the PV production and of the absolute self-consumption, for the offices building, with and without BESS, is shown in Figure 1 and Figure 2 respectively. In these figures the self-consumption curve appears a bit lower than the load curve during PV production because the charts represent an average of different levels of PV production (sunny and cloudy days).

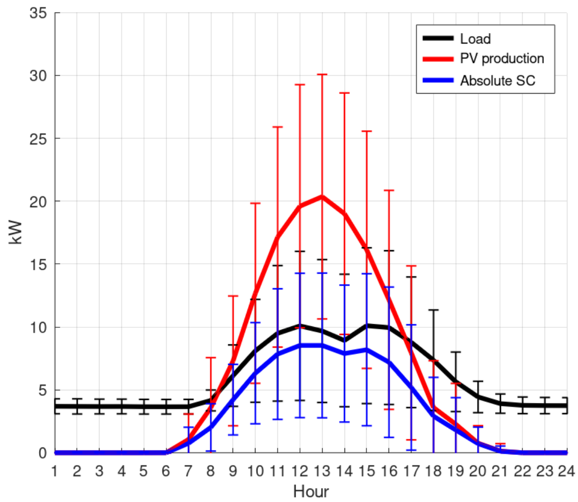

Figure 1. Average curves in offices without BESS

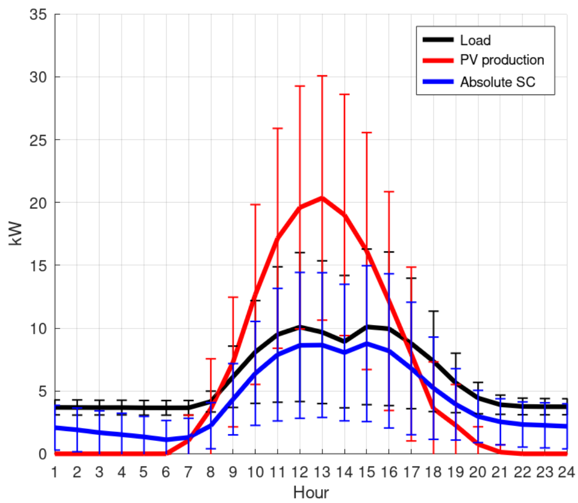

Figure 2. Average curves in offices with BESS

Figure 3 shows how SC and SS vary with different ratio between annual PV production and annual consumption.

As already pointed out, SC and SS rates are independent from this ratio, and they depend only on the shape of the load profile (besides PV performances).

In case of BESS, the diagram is valid for a fixed ratio between capacity and yearly consumption (kWh/MWh/y) of about 1.0.

SC and SS rates cross by definition when annual PV production equals annual consumption (see e.g. [3]) and this happens in this case with SC = SS = 50.3% without BESS and SC = SS = 71.2% with BESS.

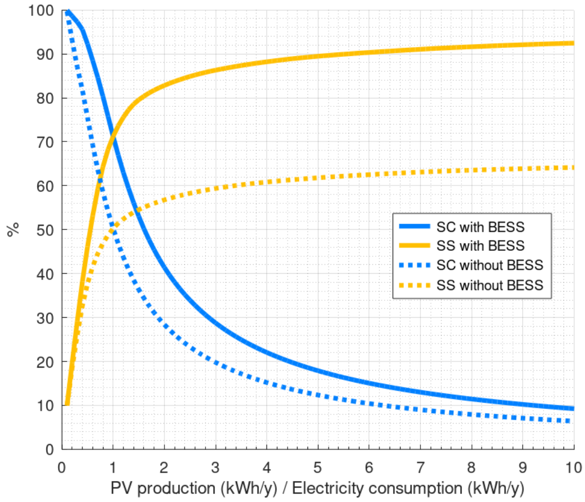

Figure 3. SC and SS in offices without and with BESS of ratio capacity/consumption = 1.0 kWh/MWh/y

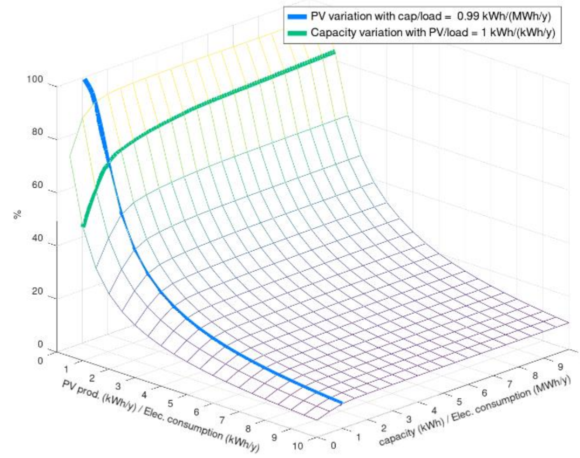

Figure 4. SC variation in office for different PV rated power and BESS capacity

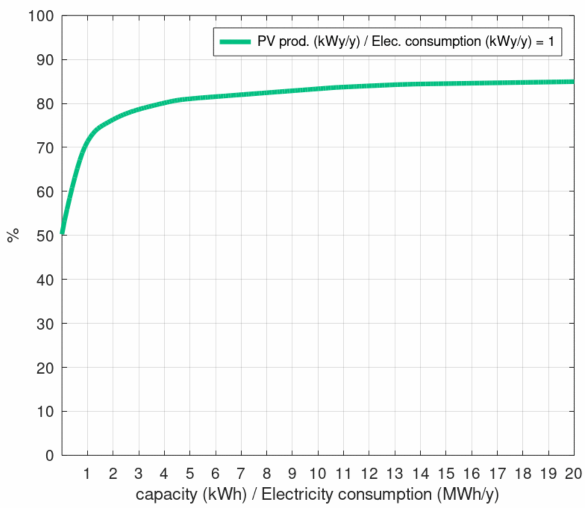

Figure 5. SC variation in office for different BESS capacities

The SS rate has an asymptotic behavior for high values of PV rated power (64% without BESS and 93% with BESS), whereas the SC rate decreases towards zero.

Figure 4 shows in a 3D graph the dependency of the SC rate on PV rated power and on the BESS capacity (normalized to annual consumption), with the typical asymptotic behavior. In case of fixed ratio between annual PV production and annual consumption, when PV production is equal to consumption, as reported in Figure 5 (also green line of Figure 4), the SC rate increases, with increasing BESS capacity, towards about the value of 85%.

A BESS capacity of 2.5 kWh/MWh/y seems enough to reach high SC rates (77%). Higher values imply only 10% of advantage of SC increase, but much higher installation costs for the BESS.

3.2 Sizing for household

Household consumption data are collected from a sample of 10 houses, residence of employees working in the building analyzed in the previous section. The representativeness of these data, as compared to the typical Italian load curve, has already been discussed by Branchetti et al. [2].

The average behavior of the load curve during the day, of the PV production and of the absolute self-consumption, for the households, with and without BESS, is shown in Figure 6 and Figure 7 respectively.

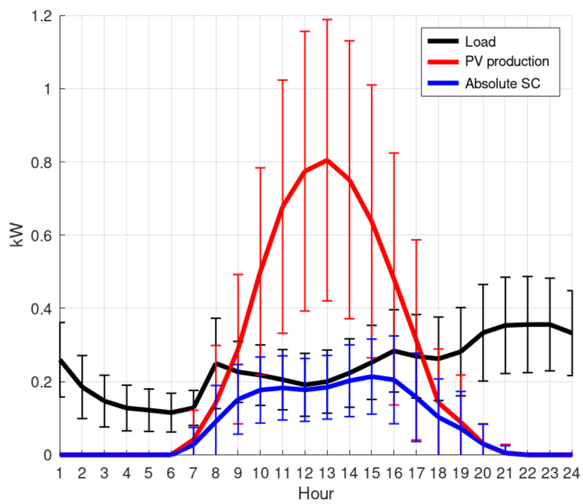

Figure 6. Average curves in household without BESS

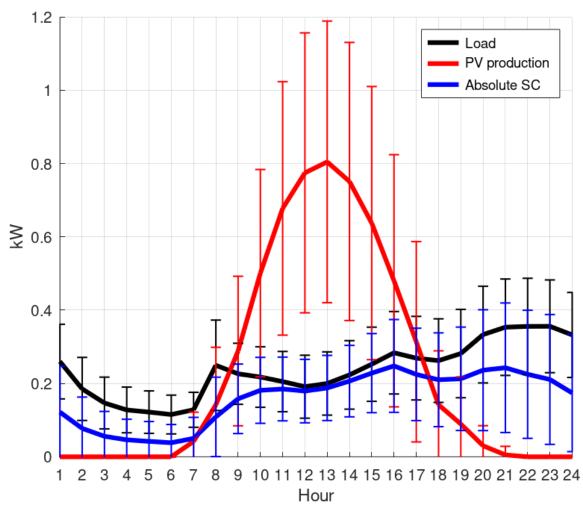

Figure 7. Average curves in household with BESS

Again, SC and SS rates cross by definition when annual PV production equals annual consumption (Figure 8). In this case, this happens at about 1.6 kWp and at the value of 34.8% of SC and SS without BESS. This value is consistent with the value (30%) found for example in the study of ref. [11] for a different residential profile in Germany. Slightly lower values are found in ref. [10] for a different residential profile in Turin-Italy (SS=38% for production/consumption=0.72, while, here, SS=46%). The Italian average SC rate for households is reported to be 35% in ref. [4].

Note that SS has an asymptotic behavior under 45% without BESS. Higher values cannot be reached.

Including BESS, sized with the method already described in Section 2.3, SC and SS rates cross at the value of 67.8% (not far from the value of 62% found by Weniger et al. [11]) and the SS asymptotic behavior is under 88%, with a ratio between capacity and yearly consumption (kWh/MWh/y) of about 1.5 (Figure 8).

The dependency of the SC rate on PV rated power and on the BESS capacity (normalized to consumption), is shown by Figure 9. For a fixed ratio of 1 between annual PV production and annual consumption, the SC rate varies for different BESS capacities with an asymptotic behavior of about 77% (Figure 10).

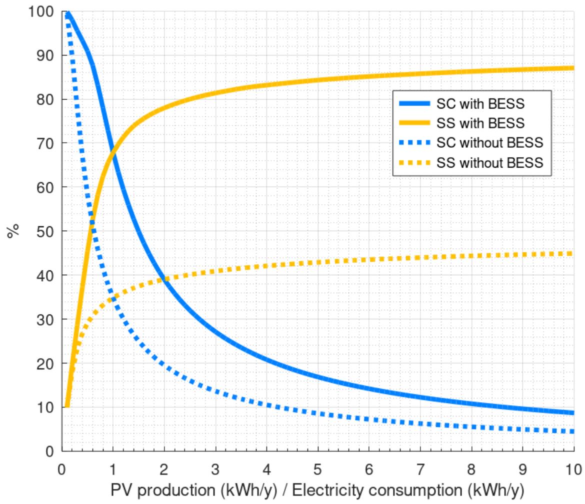

Figure 8. SC and SS in household without and with BESS of capacity/consumption = 1.5 kWh/MWh/y

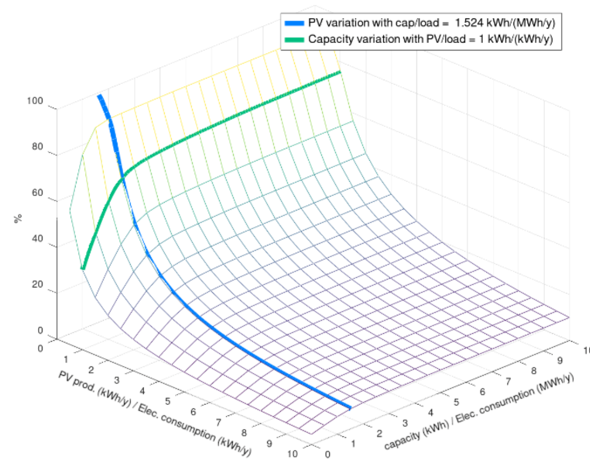

Figure 9. SC variation in household for different PV rated power and BESS capacity

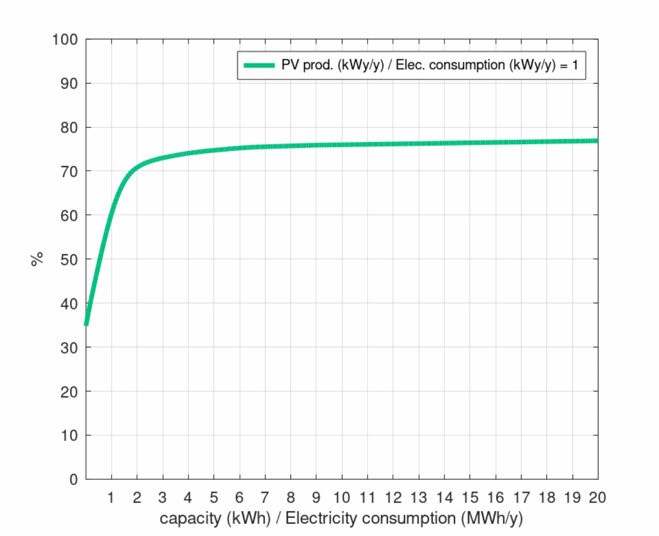

Figure 10. SC variation in household for different BESS capacities

4. IMPACT OF LOCKDOWN MEASURES ON SELF-CONSUMPTION

4.1 Description of seasonal effects

The electric load curves for office and household have been analyzed by Branchetti et al. [2] during the first "strict" lockdown period compared to the same period of the previous year. This means that the analysis is limited to only two months of the whole year (16 March – 17 May).

The seasonal effects have been evaluated by calculating the self-consumption throughout a whole year (1 March 2019 – 28 February 2020). Figure 11 and 12 plots, day by day, the absolute self-consumption, the SC rate and the SS rate, showing their seasonal behavior (due mainly to the variation of the solar irradiation), for the office and household cases, respectively. The shape of the resulting curve has been smoothed by a moving average over a sliding window of 14 points.

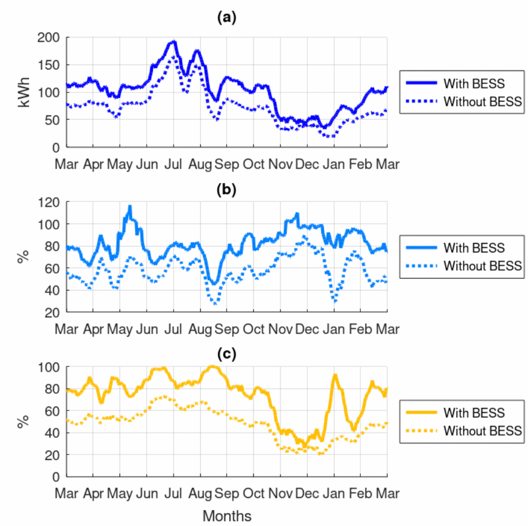

Figure 11. (a) Absolute self-consumption, (b) SC and (c) SS in office with and without BESS

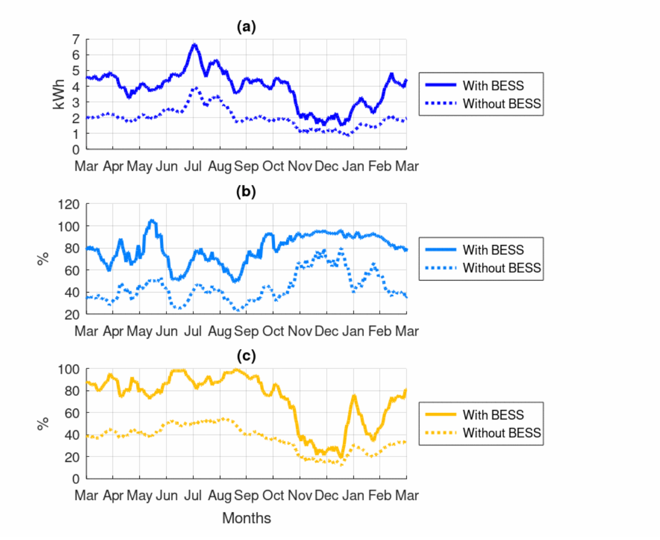

Figure 12. (a) Absolute self-consumption, (b) SC and (c) SS in household with and without BESS

In winter, the absolute self-consumption and the SS rate is at a minimum value due to low PV production, whereas the SC rate is high because almost all the produced electricity is self-consumed.

In summer, the absolute self-consumption is at its peak due to high PV production.

The daily mean and the standard deviation of the SC and the SS rates for office building and for households are reported in Table 1 and Table 2 respectively.

The average SC values in the March-May period are about 55% and 41% for office building and households respectively, without BESS, and 80 % for both with BESS, which are close to the mean annual values (respectively 57.5% and 44.5% without BESS and 81.7% and 79.2% with BESS). Therefore, the period March-May (lockdown period) can be considered to be close to the annual average value and representative of the annual behavior.

Table 1. SC and SS daily rates for office building

	Mean	**Std**
SC without BESS	57.5%	± 27.3
SS without BESS	48.1%	± 18.7
SC with BESS	81.7%	± 34.6
SS with BESS	73.6%	± 27.1

Table 2. SC and SS daily rates for households

	Mean	**Std**
SC without BESS	44.5%	± 23.1
SS without BESS	36.4%	± 14.6
SC with BESS	79.2%	± 31.6
SS with BESS	72.0%	± 29.6

4.2 Self-consumption for office buildings

In order to perform the analysis of self-consumption in lockdown period for the office building, actual monitored data of the electric load curve of office building during March-May 2020 (lockdown period) and during March-May 2019 have been used. The PV rated power has been assumed to be 42 kWp and the BESS capacity of 52 kWh, as calculated in 2.4 section.

The SC and SS rates without and with BESS for different rated power of the PV plant installed, expressed as annual PV production divided by the annual consumption, are reported in Figure 13 and Figure 14 respectively.

In case of BESS, the characteristic is valid for a fixed ratio between capacity and yearly consumption (kWh/MWh/y) of 1.0 in the 2019 period and 1.7 in the 2020 period.

As already pointed out, the SC-SS diagram curves are built to be independent from the total PV production/consumption ratio, but they depend on the shape of the load curve (normalized to total consumption). During the lockdown period, the load curve profile changed due to different resident behaviors: Figure 13 and 14 show the characteristic diagrams for the two curves (e.g. continuous blue line vs dashed blue line).

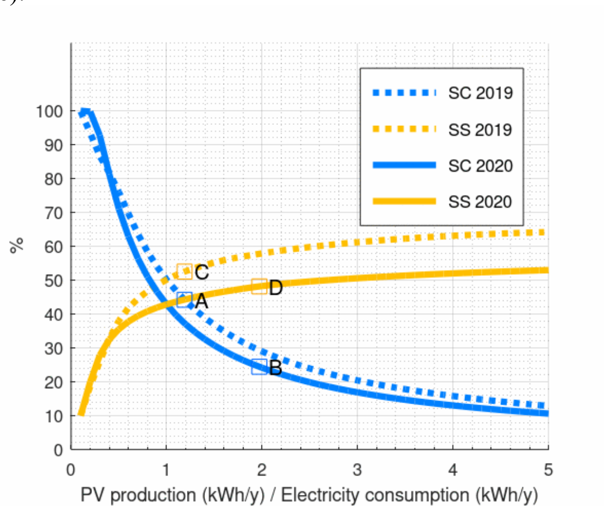

Figure 13. PV SC and SS rates in offices without BESS

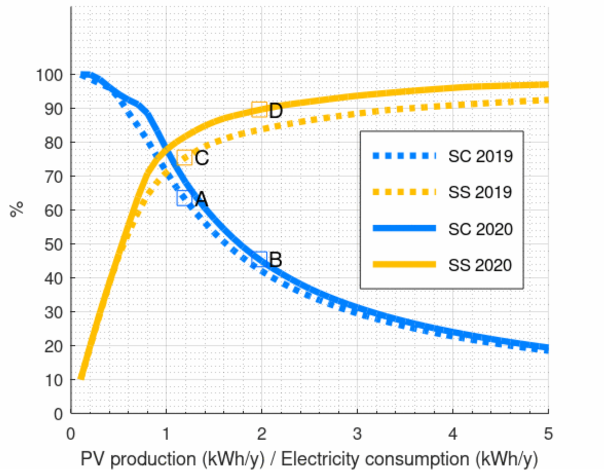

Figure 14. PV SC and SS rates in offices with BESS

The SC rates for office building, during the lockdown period, decreased, with respect to the previous year, by 20 points from 44% (point A of Figure 13) to 24% (see point B of Figure 13) [2].

With the presence of BESS, the SC rates decreased by 18 points, starting from 63% (point A of Figure 14) down to 45% (point B of Figure 14).

4.3 Self-consumption for household

Also for the analysis of self-consumption in lockdown period for households, actual monitored data of the electric load curves during March-May 2020 and during the same period of the previous year, have been used. The PV rated power has been assumed to be 1.6 kWp and the BESS capacity 3.2 kWh, as calculated in 2.4 section.

The SC and SS rates without and with BESS for different rated powers of the PV installed, expressed as annual PV production divided by the annual consumption, are reported in Figure 15 and Figure 16 respectively.

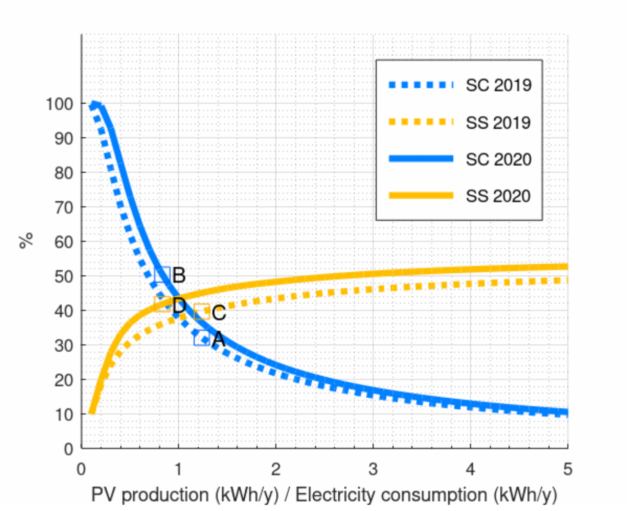

Figure 15. PV SC and SS rates in household without BESS

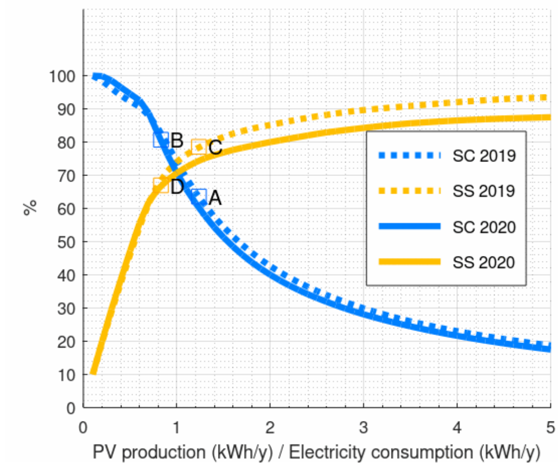

Figure 16. PV SC and SS rates in household with BESS

In case of BESS, the characteristic is valid for a fixed ratio between capacity and yearly consumption (kWh/MWh/y) of 1.7 in the 2019 period and 1.2 in the 2020 period. In [2] the SC rates for households, during the lockdown period, increased, with respect to the previous year, by 18 points from about 32% (point A of Figure 15) to 50% (point B of Figure 15).

Including BESS, the SC rates increased of about the same amount of points but starting from 64% (point A of Figure 16) to arrive at 80% (point B of Figure 16).

5. DISCUSSION

The analysis performed in section 3, based on yearly data (Figure 3 and Figure 8), shows that high values of PV rated power increase the values of SS, making more energy available to be self-consumed, but lower the values of the SC rate (because the PV production, in the denominator, increases more than the numerator, that is the absolute self-consumption). This is valid for both office building and household profiles.

All the SC-SS curves have an asymptotic behaviour with high values of the rated PV plants. In particular, the SS rate, without BESS, has an asymptotic behaviour towards 64% for office building and 45% for household. Higher values cannot be reached because nocturnal consumptions, as well as daily consumptions in cloudy days, cannot be supplied by the PV panels, no matter how high the power installed. For example, planning a PV such that PV production/consumption > 1.5 in household (corresponding to SS=38% and SC=25%) involves low benefits on SS, lower SC values and higher investment costs. For a complete analysis other economic variables are to be calculated (Net Present Value, Return of Investment, etc.), which are planned as development of this work.

With the adoption of BESS, sized in such a way that the capacity corresponds to the difference between the PV production curve and the load curve (ratio of 1.0 and 1.5 kWh/MWh/y for office building and household respectively), the SS rate has an asymptotic behaviour towards 93% for office building and 88% for the households.

When PV production equals annual consumption, without BESS, the SC and SS curves cross at 50.3% for office building and at 34.8% for households, whereas they match at 71.2% for office building and at 67.8% for household including BESS.

The analysis of the data in the lockdown period, developed in section 4, shows variation of SC rates, that can be envisaged to be due to 2 separated effects: The increase of the absolute consumption (kWh/month) (people stayed at home) and the change of the normalized load shape (e.g. higher values during working and evening hours at home).

The first effect (change of production/consumption) shifts the SC along the right or left side following the blue lines (see Figures 13-16): decreasing the absolute total consumption raises the ratio PV production/consumption and therefore the SC rates decrease, whereas increasing the absolute total consumption, the ratio PV production/consumption decreases and therefore the SC rates increase (left side of the figures). The impact of this effect can be quantified in about -13 points for the office building and +15 points for the households.

The second effect (change of the shape of the normalized load curve) creates a second characteristic SC curve, close to the original one, here shown as the continuous lines, and can be quantified in about -7 points for the office building and +4 points for the households.

The separation of these effects is considered here important because it allows to understand whether the change of the SC rate is due to different consumption (and can be compensated by a different PV size) or to different behaviour of the users.

The SS rate, without BESS, does not vary significantly during the lockdown period with respect to the previous year.

Table 3. SC and SS rates for office building

Lockdown period (16/03-17/05)	Self-cons. rate 2019	Self-cons. rate 2020 (lockdown)	Changes
SC without BESS	A = 44.2%	B = 24.4%	- 19.8 points
SS without BESS	C = 52.5%	D = 48.2%	- 4.3 points
SC with BESS	A = 63.4%	B = 45.4%	- 18.0 points
SS with BESS	C = 75.3%	D = 89.5%	+14.2 points

Instead, including BESS, the SS rates in lockdown period show a change of +14.2 points (Table 3) and of -11.7 points (Table 4) for office building and household respectively, and this is due to the change of the consumption, the change of the profile and the BESS capacity.

Table 4. SC and SS rates for household

Lockdown period (16/03-17/05)	**Self-cons. rate 2019**	**Self-cons. rate 2020 (lockdown)**	**Changes**
SC without BESS	A = 32.1%	B = 50.4%	+18.3 points
SS without BESS	C = 39.6%	D = 41.8%	+ 2.2 points
SC with BESS	A = 63.5%	B = 80.4%	+16.9 points
SS with BESS	C = 78.4%	D = 66.7%	- 11.7 points

6. CONCLUSIONS

The lockdown periods during the COVID-19 pandemic had impact also on the electric consumption, shifting the energy demand from tertiary sector to residential users.

In this paper the consequences of this change on SC and SS rates are analyzed when PV plants are installed, also in presence of BESS, whose adoption has the goal of increasing self-consumption and of decreasing the energy exchange with the electric grid and therefore the grid stress.

The motivation of this analysis derives from the fact that installation of PV plants is increasing, due to global commitments to raise the energy contribution from renewable energy, and the homeworking is becoming more common, after the COVID-19 pandemic, also with the goal of reducing daily commuting.

In order to analyze the SC and SS rates it is very useful to consider the SC-SS characteristic curves, as function of the ratio PV annual production/consumption (kWh/kWh) and the ratio BESS capacity/consumption (kWh/MWh/y). This normalization approach is valid under the assumptions of a simplified BESS simulation model and when no grid injection limits are foreseen.

These curves depend, besides specific PV performances and location, on the form of the normalized active power load (distribution along the hours of the day). Different characteristic curves are determined by different shape load profiles and therefore for example by different behavior of the residential users and adoption of domestic appliances.

In this way it is possible to grasp a global comprehension of SC and SS behavior, understand and control simultaneously the impact of the change of different variables: electric consumption, different PV rated powers, BESS with different capacities, while avoiding sparse and fragmented calculations. The results can thus be used also when considering group of families (e.g. an apartment building of 50 flats) and not only one family.

Office and residential behaviors and characteristics curves have been analyzed, with and without BESS. The shape of the load curve in the offices (higher values in the range 11 am – 4 pm), of course, is very different from the one of the residential users (higher values at 8 pm – 11 pm). In the offices, the electric load curve matches better the PV production curve.

Setting the PV production to be equal to the annual consumption, with the adoption of BESS (sized with the method described in Section 2.3), the annual SC rate increases from 35% to 68% in case of households and from 50% to 71% in case of the office building.

During the lockdown period, the SC rate, with and without BESS, decreases by 17-20 points in office building (Table 3) and increases by comparable values in households (Table 4). Without BESS, the lockdown effect increases the SC by 18 points in households and this can be separated into two contributions: the change of the load profile (5-7 points) e and the increase of consumption (10-14 points).

With the regards to SS rate, its value does not vary significantly both in office building and in households without BESS. Whereas, in presence of BESS, in the office building it increases by 14 points, but this does not compensate the loss of the SC rate (-18 points). While at home the SS rate decreases of 12 points, but the SC increases of 17 points.

If PV is sized such that annual PV production is equal to consumption, without BESS, then the SC (=SS) rate increases from 38% to 43% in households and decreases from 50% to 43% in office building. Including BESS, the SC (=SS) rate decreases from 74% to 71% in households and increases from 71% to 78% in the office building.

The size, performances and therefore the economic parameters of the PV plants are then influenced by homeworking and this fact has to be taken into account when planning new PV plant installations.

Of course, the use of BESS mitigates the consequences of the variation of the load curve due to homeworking and to other changing habits.

An interesting situation is obtained by sharing, among different office and residential users, the energy production and the BESS systems, thus mixing the load and production curves and compensating some effects. This topic will be developed in future works.

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NOMENCLATURE

GHG	Greenhouse Gases
BESS	Battery Energy Storage System
SC	Self-Consumption
SS	Self-Sufficiency
PV	Photovoltaic
kWp	kilowatt-peak
y	year
SOC	State Of Charge