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Strategies, Costs, and Benefits for Achieving Energy Self-Sufficiency in the Italian Manufacturing Sector With PV Technology[#]

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ABSTRACT

This research investigates the feasibility of achieving electricity supply self-sufficiency for manufacturing companies through the integration of photovoltaic (PV) systems and energy storage solutions. The article uses a static energy balance model and optimization procedures to assess two case studies of small- and medium-sized metalworking companies in northeastern Italy. The following critical ideas are addressed: the viability of PV-based self-sufficiency, the influence of demand-side management on system performance, and the cost-effectiveness and carbon footprint of self-sufficient PV installations compared to traditional energy supplies.

Keywords: Energy self-sufficient factories, photovoltaic systems, demand-side management, carbon footprint

NOMENCLATURE

BESS	Battery Energy Storage System
BOS	Balance of System
DOD	Depth of Discharge
DSM	Demand-Side Management
NPV	Net Present Value
PV	Photovoltaic
PVGIS	Photovoltaic Geographic Information System
RQ	Research Question

1. INTRODUCTION

Traditional energy management in manufacturing is based on centralized, unidirectional systems. However, in the "age of disruption," with geopolitical uncertainties and climate change, established sources of supply are changing [1]. Renewable energy sources, such as photovoltaic (PV), are typically uncertain and volatile upon entering the mainstream energy sector, but they may be inexpensive enough for large prosumers to defy the grid [2]. Self-sufficient factories, systems that do not receive energy from the grid [3], are believed to be more sustainable. However, designing such facilities is challenging because they require integrating renewable energy, energy storage, efficiency measures, and flexibility. While studies have investigated the feasibility of achieving energy self-sufficiency in residential [4] and commercial [5] buildings, research on self-sufficient factories [6, 7] is limited and very recent. Some studies on this topic focus on flexibility and demand side management (DSM) measures, which are typical features of renewable energy applications in industry. Literature often prioritizes technical and economic performance [7, 8] while largely overlooking environmental performance indicators, such as the carbon emissions of industrial systems. Furthermore, the carbon emission indicators may be limited to operational emissions, as in references [4] and [5], which take no account of the embedded carbon in the manufacture, installation and replacement of the PV infrastructure and battery energy storage system (BESS). This factor could become significant, given the magnitude of electricity demand in industrial settings.

Provided this background, the following research questions (RQ) emerge:

RQ1. Can typical, “less energy-intensive” [9] manufacturing industries be self-sufficient in terms of their electricity demand by using only their PV roof systems?

RQ2. To what extent can DSM measures, such as changes in production schedules, affect the economic and environmental performance of PV-based renewable electricity supply to manufacturing companies?

RQ3. Is PV-based self-sufficiency cheaper than a conventional energy supply to the extent that grid defection (not connected to the grid, cannot buy or sell) becomes an option, or does it incur additional costs for companies?

RQ4. What are the environmental benefits, such as reducing carbon footprint, or the costs of striving for PV-based self-sufficiency?

This study addresses these research questions by focusing on two companies in the metalworking sector in northeastern Italy.

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2. MATERIALS AND METHODS

Hourly electricity consumption data was collected for the year 2023 from two Italian metalworking companies, both prosumers (produce and use electricity). One is a reference small prosumer with a maximum rooftop area of 3000 m^2 and an annual consumption of 426.4 MWh, and the other considered as a reference medium industrial prosumer with a maximum rooftop area of 15000 m^2 and an annual electricity consumption of 642.4 MWh. As shown in Figure 1 of an average week, peak industrial demand typically occurs around midday on working days and a flat minimum demand occurs on Sundays, with the medium prosumer exhibiting a more remarkable variance.

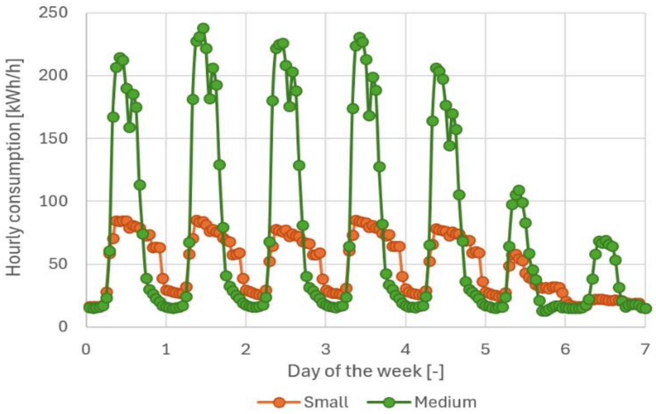

Fig. 1 Average weekly load profile of reference industrial buildings on an hourly basis

2.1 *Energy system model*

A static energy balance simulation model was developed in Excel VBA to enable quick component sizing, simulation of produced, shared and purchased electricity, and assessment of corresponding carbon emissions over the system's lifetime. The Photovoltaic Geographical Information System (PVGIS) [10] was used to evaluate hourly PV energy production. Solar radiation data of five recent years (2016-2020) was obtained from the PVGIS-SARAH2 dataset and averaged. Relevant literature [11]-[13] was reviewed for PV system component expected lifetimes, efficiencies, and carbon footprints, as summarized in Table 1. All components were presumed to be new and recently installed; mono-crystalline silicon PV panels, which currently dominate the global market, were used. The hourly emission factors reported in [14] were used to evaluate the carbon equivalent emissions resulting from electricity purchases and sales credits for each time step. Personal communications from installers were used to calibrate the literature-based cost functions reported in Table 1.

To assess the carbon footprint, a lifetime of 25 years was assumed for panels, inverter, and mounting structures. In line with [15], the degradation of PV panel energy productivity was accounted for by assuming a power degradation rate of 0.5% per year.

2.2 *Optimization model*

The second step of the methodology involved sizing the factory energy supply system to maximize profitability and, in a dedicated scenario, to meet a 100% load-based self-sufficiency constraint. We combined the simulation model with an optimization procedure using Evolver 7.5.1, a commercial software add-in for Microsoft Excel [16].

Table 1 Energy, economic and environmental parameters

PV System component	Lifetime [years]	Efficiency	Cost function [€]	Carbon emission factor [kg CO_2eq/kWp]
Mono-crystalline PV panel	25	18%	$1661 \cdot P^{0.919}$	643.7
Inverter and BOS	25	96%		119.2
Mounting structure (flat rooftop)	25	-		342.7
Mounting structure (ground mounted)	25	-	$1.2 \cdot 1661 \cdot P^{0.919}$	665.5
Battery Energy Storage (LiFePO4)	13	95% charge, 95% discharge. DoD = 80%	$1123.74 \cdot P^{0.795}$	139.7

Evolver uses genetic algorithms to solve linear and non-linear optimization problems.

The decision variables and constraints in the model include:

- The peak load capacity of the PV panels to be installed on the industrial prosumer's rooftop, constrained to the available flat rooftop surface area and assuming a 40° slope angle, a 25° angle limit, and south facing panels

- The maximum number of ground mounted PV panels that can be installed, limited by the maximum available surrounding area (30,000 m² for the small-sized company and 100,000 m² for the medium-sized company). Ground mounted PV are used in RQ2 - RQ4.

- The capacity of the BESS (lithium batteries) to be installed at the industrial site, with an upper bound of 50,000 kWh.

The objective function is to maximize the system net present value (NPV), considering credits from electricity sales at the average exchange price for Northern Italy, based on historical data for 2023. The NPV is calculated over 25 years at an interest rate of 10%. The batteries are assumed to be replaced after 13 years.

2.3 *Scenario based calculations*

Regarding RQ1, the simulator assumed that the panel surface area is sized to the maximum roof space available, as previously demonstrated by [6] for 36 Chinese industries. Then, the capacity of the installed BESS was varied and the self-sufficiency rate, i.e. the percentage of self-consumption over total annual demand, was calculated. Selling excess energy at market price was always permitted, meaning the system can be self-sufficient on a load basis but still contribute to the grid.

Next, RQ2 evaluates the impact of DSM measures on the small and medium companies. The optimizations were launched for the baseline scenario (denoted as 0) and when the start time of work was advanced or delayed by one or two hours, obtaining the DSM scenarios denoted as -1, +1, -2, +2, respectively. It was assumed that the shapes of the load profiles would remain unchanged and they would only be shifted. For RQ2 – RQ4, the optimization procedure uses the maximum rooftop space available for each company and the maximum available surrounding areas as upper bounds.

Next, to study the effect of self-sufficiency on economic performance (RQ3), the optimizer was first used to determine the highest NPV configuration of each company for the baseline and DSM scenarios (±1, 0, ±2), respectively. The optimizations were then repeated under the constraint of achieving a 100% self-sufficiency rate. The comparison of NPVs between the two options allows to determine the increase or decrease in net economic benefits when self-sufficiency constraints apply.

Lastly, regarding RQ4, we assessed the carbon footprint including both the impact of operations and of equipment manufacturing. The assessment was performed for all the economically optimized configurations (baseline scenario 0 and DSM scenarios ±1 and ±2), both with and without the 100% self-sufficiency constraint.

3. RESULTS AND DISCUSSION

RQ1: When a system depends solely on available roof space, energy self-sufficiency largely hinges on the dimensions of the roof. Provided that the proportion between the usable rooftop space and the yearly energy demand is considerably higher for the medium- than for the small-sized enterprise (approximately 23 m^2/MWh as opposed to 7 m^2/MWh, respectively), 100% self-sufficiency can be attained in the medium-sized but not in the small-sized enterprise. In both cases, no additional self-sufficiency advantage is achieved beyond a battery energy storage system (BESS) capacity of 3000 kWh. Figure 2 shows the self-sufficiency rate of the small- and the medium-sized companies as battery capacity varies.

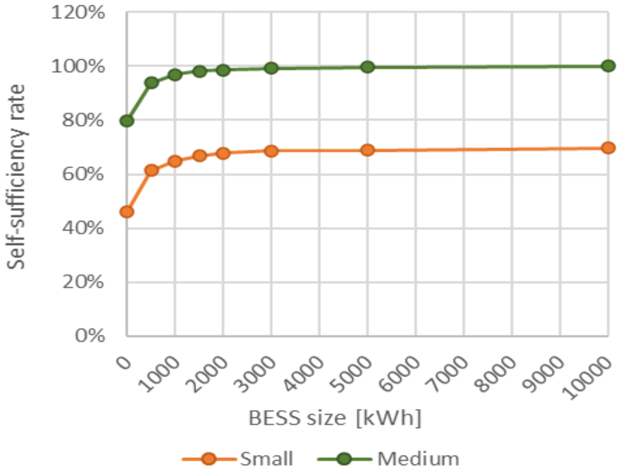

Fig. 2 Self-sufficiency rate with maximum size rooftop-based PV systems by varying BESS size

RQ2: Table 2 shows the self-sufficiency rate and the amount of energy sold to the grid for the optimal solutions for baseline and alternative DSM scenarios. The optimization procedure tests combinations of roof- and ground-mounted panels, as well as battery capacities in kilowatt-hours, to identify the combination with the highest NPV. Eight combinations were explored: small or medium company with or without self-sufficiency and selling (System NPV, no revenues) or not selling energy (System NPV with revenues). The optimal (BESS), rooftop, and ground-mounted sizes are presented in Table 2, and the corresponding NPVs are reported in Table 3 for all combinations and DSM scenarios.

Note that a BESS is only introduced when self-sufficiency is imposed because the economic value of avoiding grid purchases does not offset the BESS cost. The optimal battery sizes are similar for small and medium-sized companies.

For the small-sized company, the optimal battery size varies little with the production schedule. The highest self-sufficiency rate is achieved by starting operations one hour earlier, which also minimizes the required battery size.

On the other hand, for the medium-sized company the impact of load shifting on the optimal battery size is substantial and the current start time requires the smallest battery. In both case studies, most of the energy produced is sold, ranging from a minimum of 87.6% for the small-sized company with a self-sufficiency constraint to a maximum of 95.9% for the medium-sized company without any self-sufficiency constraint. In all cases, the maximum possible panel capacity is installed, demonstrating that the sale of excess-produced energy is always favorable. This is confirmed by the positive NPVs considering grid sales revenues, as reported in Table 3. As can be seen, shifts in production schedules either worsen the economic performance of systems, whether or not revenues are considered, or result in minimal improvements (below 2%).

Environmentally, Figure 3 shows that the variations linked to different load shifting strategies are essentially negligible except insofar as they confirm that starting work two hours later would be the worst possible strategy in all circumstances

Table 2 Least-cost configurations for systems with and without self-sufficiency constraints

		Hours shift	Ground PV [kW]	Roof PV [kW]	Battery size [kWh]	Self suff. rate	Sold to produced energy
Small	W/O Self-suff. constraint	-2	2518.1	251.8	0	59.6%	92.6%
		-1				59.9%	92.6%
		0				59.2%	92.7%
		+1				57.0%	92.9%
		+2				54.0%	93.3%
	With Self-suff. constraint	-2	2518.1	251.8	1300	100.0%	87.6%
		-1			1270		
		0			1291		
		+1			1281		
		+2			1354		
Medium	W/O Self-suff. constraint	-2	8393.5	1259	0	76.3%	95.9%
		-1				81.9%	95.6%
		0				83.8%	95.5%
		+1				81.4%	95.6%
		+2				76.3%	95.9%
	With Self-suff. constraint	-2	8393.5	1259	1349	100.0%	94.6%
		-1			1092		
		0			976		
		+1			1224		
		+2			1696		

Table 3 NPVs with and without sales revenues depending on DSM scenarios. The best DSM strategy, highlighted in yellow, corresponds to the percentage improvement from the baseline (0) which is reported as "max % gain"

		Small		Medium	
		System NPV, no revenues	**System NPV, with revenues**	**System NPV, no revenues**	**System NPV, with revenues**
w/o self-sufficiency	**max % gain with best DSM**	**0.45%**	**1.65%**	**0**	**0**
	-2	-2,801,393 €	653,584 €	-9,510,379 €	2,953,195 €
	-1	-2,806,922 €	645,898 €	-9,434,195 €	2,988,105 €
	0	-2,813,934 €	642,955 €	-9,416,578 €	2,998,708 €
	+1	-2,834,765 €	634,667 €	-9,461,688 €	2,985,058 €
	+2	-2,864,924 €	622,959 €	-9,544,388 €	2,955,278 €
with self-sufficiency	**max % gain with best DSM**	**0**	**1.17%**	**0**	**0**
	-2	-9,510,379 €	200,197 €	-9,771,287 €	2,459,734 €
	-1	-9,434,195 €	198,862 €	-9,671,005 €	2,577,775 €
	0	-9,416,578 €	202,087 €	-9,632,896 €	2,630,545 €
	+1	-9,461,688 €	204,443 €	-9,734,145 €	2,537,745 €
	+2	-9,544,388 €	174,354 €	-9,906,671 €	2,365,381 €

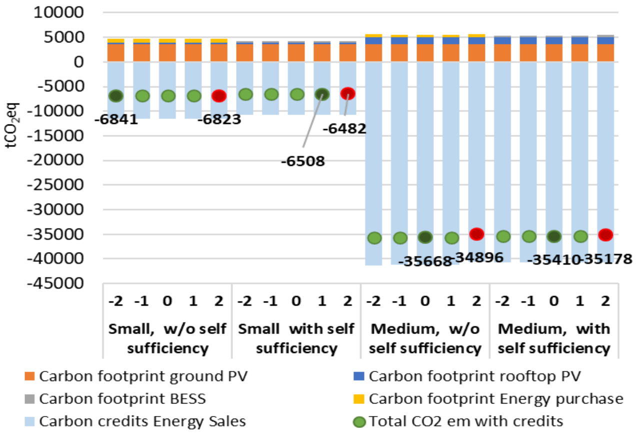

Fig. 3 Life cycle carbon equivalent emissions of optimized configurations depending on load shifting strategy and self-sufficiency constraints. DSM scenarios with the highest and lowest net equivalent emissions are marked with red and dark green bullets, respectively

In short, these calculations confirm that, as shown in Figure 4 for a medium sized company and a typical winter week, the time span of maximum demand aligns well with the time span of maximum generation from PV panels.

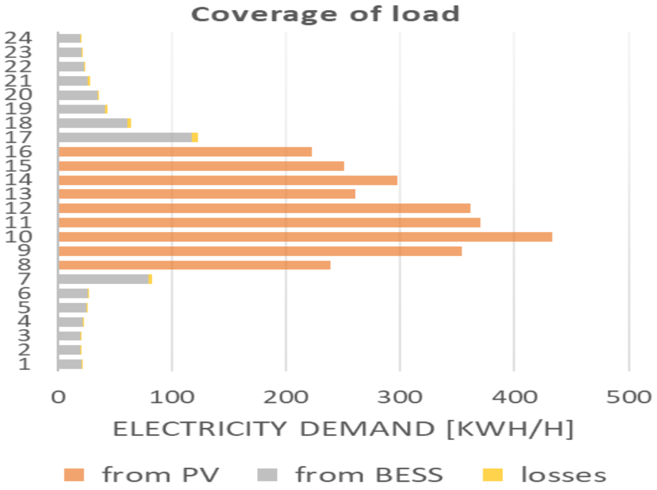

Fig. 4 Load coverage under self-sufficiency conditions for the medium-sized company in a typical winter week

RQ3: By comparing the NPVs of optimal solutions with and without self-sufficiency constraints, we observe that the NPVs of optimal systems with self-sufficiency constraints are always significantly lower than those without. The corresponding reductions in NPV range between 218 k€ (medium company, not considering revenues) and 6700 k€ (small company, not considering revenues).

As a result, load-based self-sufficiency is not a feasible option for the examined companies from an economic viewpoint, and grid defection is even less so. In fact, the same combination of ground-mounted and rooftop-mounted panels is selected, whether or not self-sufficiency constraints are imposed, and this selection corresponds to the upper bounds imposed. In other words, maximizing NPVs with revenues in all optimization scenarios results in installing maximum capacity panels. This choice enables self-sufficiency, even during the winter months, by introducing a properly sized battery energy storage system (BESS) that can be completely recharged within the first few hours of the morning, as shown in Figure 5 for a typical winter week. The BESS can thus meet the low nighttime demand shown in Figure 4 for the same week.

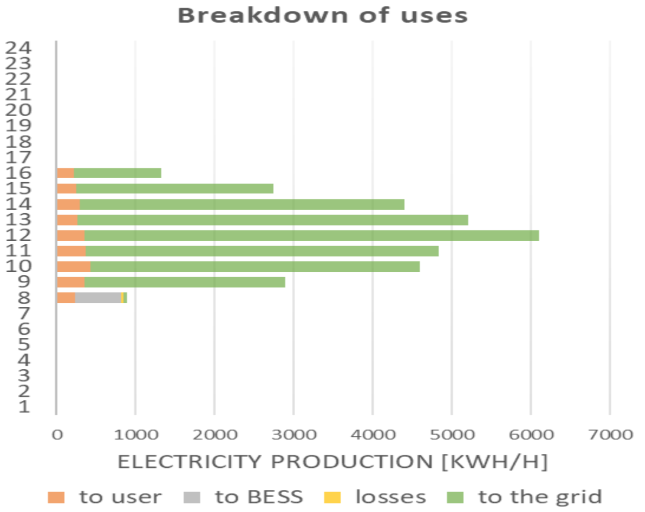

Fig. 5 Breakdown of final uses of the electricity produced at the medium-sized company for a typical winter week under self-sufficiency constraints

However, although such system is self-sufficient in terms of self-consumption, it is strongly linked to a grid capable of absorbing excess energy (bars in green in Figure 5) in order to achieve profitability, as can be deduced by the comparison of the system NPVs with and without revenues reported in Table 3.

RQ4: From an environmental perspective, Figure 3 shows that achieving self-sufficiency results in a 4% increase in net emissions over the life cycle for the small company and a negligible increase for the medium company. The embedded emissions of battery energy storage systems (BESS) (shown in grey in Figure 3) are generally offset by avoided emissions from not purchasing electricity (shown in yellow in Figure 3). However, pursuing a self-sufficiency strategy results in a decrease in carbon credits from electricity sales, creating an unfavorable net balance.

4. CONCLUSIONS

We implemented a simulation model to minimize net LCC through optimizing PV system and BESS size, start time of industrial operations, and sale of energy. The model was applied to two case studies of real, non-energy-intensive manufacturing companies located in Northern Italy.

RQ1 assessed the conditions under which these companies could achieve electric consumption using only rooftop PV panels. It is possible for the medium-sized company, but not the small-sized company due to the ratio of roof area to consumption. While the battery is essential for achieving 100% self-sufficiency, it does not make a significant contribution above a certain capacity. A combination of roof-mounted and ground-mounted system would be required for the small-company to be self-sufficient.

To investigate the impact of demand-side management strategies (RQ2), we simulated shifting the start of production by±1 or ±2 hours. These shifts were found to have a limited impact on battery size and system economics for the small-sized company examined. Nevertheless, existing load profiles are generally well aligned with potential solar generation, so shifts are not advisable. This is especially true for the medium-sized company examined. In this respect, a clear limitation of this study is that our analysis is based on two companies which have one operating shift during the day. Future developments will include a larger sample of companies, particularly companies with night shifts, as is often the case in large-scale process industries.

These developments are also relevant for a more in-depth assessment of RQ3, which focuses on achieving load-based self-sufficiency or even grid defection. While PV-based self-sufficient systems have been shown to be technically feasible, they are more expensive than equivalent systems without batteries. Therefore, reducing the nightly load is crucial to keeping battery costs low. In our case, even self-sufficient systems are cost-effective compared to traditional electricity supplies when factoring in revenues from electricity sales, as the net present values (NPVs) are consistently positive. However, this could change with different load profiles, resulting in larger and more expensive battery energy storage systems (BESS). It could also change with different selling price patterns or climate conditions. Zones with lower solar irradiation than Northern Italy would be especially affected, negatively impacting PV energy generation and profitability. A future step of this research will involve simulating these circumstances and optimizing the system under unfavorable price conditions, including full grid defection (zero selling price). These additional scenarios should also be explored from an environmental perspective. Our carbon footprint calculations for the examined companies, which include embodied emissions for equipment manufacturing, have shown that substantial reductions in net carbon equivalent emissions can be achieved with large and complex PV-based systems, even those with large batteries. This is primarily due to carbon credits from energy sales. However, complete self-sufficiency may increase net carbon emissions, as demonstrated by the small firm (RQ4).

In summary, applying the model provides interesting insights into the economic and environmental value of self-sufficiency. In particular, it is shown that self-sufficient factories still depend on the grid for the resale of surplus energy.

Future developments will include a larger sample of companies, determining the optimal PV system size if selling is not an option (island mode) and assessing companies with different load profiles, multiple operating shifts or under different climate conditions. Since the ratio of available rooftop area to consumption appears critical to self-sufficiency, future research will focus on collecting and analyzing statistical data and elaborating functional relationships to estimate these values, at least for the Italian context.

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