Coordination of Optimal Sizing of Energy Storage Systems and Production Buffer Stocks in a Net Zero Energy Factory

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Abstract

Green smart factories will be one of the key elements of the future smart grids. They will play an active role in managing the volatility of power generated by renewable energy sources (RES). In order to do that, the green smart factories must set up energy management systems to control the production processes according to both the on-site power generation by RES and external signals sent by the system operators. The aim of the study is to size energy storage systems and production buffer stocks as the flexibility options, allowing the highest integration of power generated by volatile energy within a manufacturing system. The concept of the net zero energy factory is considered. Algorithms for coordinating the flexibility options optimally have been developed. These algorithms are based on mixed-integer linear programming and aim to maximize the matching between RES power generation and flexible demand. A case study is used to verify the framework results. Key performance indices, such as the system self-sufficiency index and the system self-consumption index have been considered for evaluating the solutions developed. Finally, sensitivity analysis has been performed to assess the robustness of the solutions found.

Keywords: Net Zero Energy Factories, Flexibility options, Energy Storage Systems, Optimal Manufacturing Scheduling, Production Buffer Stock, Renewable Energy Sources

1. Introduction

The global warming process has pushed many politicians to develop new national energetic strategies aiming to decrease the emission of greenhouses gases into the atmosphere. The increase of energy-efficient devices and power generation (electric and thermal) by using renewable energy sources (RES) has been the common denominator of almost all energy strategies developed. More than 1080 GW of RES-based power plants were in operation worldwide in 2017, excluding hydropower technology [1]. Many governments offered economic incentives to the generation of electric power by RES to support the power generated by these sources.

Many enterprises, mostly in Europe, have identified an attractive business model in such a governmental policy for adding new economic income. Consequently, many small, medium

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List of Symbols

ΔP^t_{grid}	Grid power consumption
δ^t_{del}	Manufacturing system production control
δ^t_{ch}	Energy storage charge control
δ^t_{dch}	Energy storage discharge control
$\delta^{i,t}_{\text{idle}}$	Process idle control
$\delta^{i,t}_{\text{prod}}$	Process production control
η_{ch}	Charge efficiency
η_{dch}	Discharge efficiency
$\overline{T^{\text{sub}}}$	Average time for off state of subcritical processes
ξ	Demand benefit factor
B^i	Production buffer stock i
c_{dch}	Cost of discharge
C_{stge}	Energy storage capacity
Cp^i_{max}	Capacity of production buffer stock i
$Cp^{\text{crit}}_{\text{max}}$	Critical buffer maximum capacity
$Cp^{\text{sub}}_{\text{max}}$	Subcritical production buffer stock capacity
Cp_{min}	Minimal inventory of production buffer stock i
E_{max}	Maximum depth of discharge
E_{min}	Minimum depth of discharge
h	Discharge time
$i = 1, \ldots, N$	Production process index
j	Continuous process index
L^t	Manufacturing system power demand
L^t_{C}	Total continuous processes power demand
L^t_{D}	Total discrete processes power demand
L_{nom}	Reference demand profile
n^{crit}	Rate of production of bottleneck process
$n^{i,t}$	Process production rate
n_{del}	Customer extraction rate
$n^{\text{sub}}_{\text{max}}$	Average rate of production of subcritical processes
$P^{\text{nom}}_{\text{pv}}$	PV Installed power capacity
P^t_{ch}	Energy storage charge power
$P^{j,t}_{\text{C}}$	Continuous process power demand
P^t_{dch}	Energy storage discharge power
P^i_{idle}	Idle power demand of process i
P^i_{off}	Off power demand of process i
P^i_{prod}	Production power demand of process i
P^t_{pv}	PV power
p^t_{pv}	Normalized PV power
P^t_{soc}	Energy storage state of charge
P_{stge}	Energy storage nominal power
S^i	Production process i
$s^{i,t}$	Production process cycle time
s_{del}	Customer cycle time
T	Time slot length
t	Simulation time
$T^{\text{crit}}_{\text{max}}$	Maximum Flexibility time
$x^{i,t}_{\text{buff}}$	Fill level of production buffer stock i

and large enterprises have become prosumers, since they can also generate electric power. Such enterprises do not generally have any energy management system (EMS) which controls the power generated, but it is firstly fed into the grid and successively withdrawn from the grid to cover the electric loads. Such inefficient *modus operandi* create challenges for the system operators, which, in many cases, are obliged to integrate the power generated by RES into the grid [2]. In addition, this approach is very expensive and, consequently, it will probably be used less. Indeed, such a way of operating the on-site generators based on volatile RES has been allowed in many European countries for the last 20 years. Many European system operators have suggested that the prosumers should pay a charge to them at the expiration of this allowance in the case where they feed the network. A lot of factory operators will probably not be allowed to feed the generated power into the network as "feed it and forget it" in the next five to ten years without additional expenditure. It is, therefore, clear that new flexibility options need to be developed and tested if a high amount of volatile power generation has to be integrated into the electric grid [3].

Among the flexibility options, the active participation of small, medium and large enterprises controlling their loads according to the power generated by RES might offer a high contribution to the integration of volatile RES into the grid [4] and might be a fundamental solution for the development of future smart grid systems [5]. Most recent research on the implementation of the active participation strategies of the industrial prosumers intend to design methodologies and models for manufacturing processes. New functionality for demand response (DR) programs have been evaluated. The dynamic of the manufacturing process transitions and the electricity price has been simultaneously taken into account in [6]. In [7], the DR programs developed take the critical peak pricing for scheduling the manufacturing processes as signal. Dynamic electric prices have been considered as an input signal for developing DR programs within manufacturing processes in production logistics [8]. In [9], the DR schedules the manufacturing process by giving priority to self-consumption.

Economic and ecological factors have been considered in [10] as the main criteria for evaluating the performance of the DR developed. In [11] and [12], DR programs have been developed for scheduling the manufacturing process and the on-site power generation optimally, aiming to minimize the factory's energy costs and to maximize the economic income. In [13], the manufacturing process has been scheduled according the power generated by on-site RES power plants. The minimization of electricity costs by controlling the single machines of the manufacturing process has been the focus of the DR programs tested in [14]. The DR programs developed according to the ecological criterion have been tested in [15] and [16]. Strategies based on the control of manufacturing processes are generally the most flexible [13]. An optimal production schedule and on-site generation utilization schedule can be obtained, and the real application presented demonstrates the benefits of optimized load management for energy and economic savings.

Although most of the methods proposed have added to the problem of integrating the volatile renewables, a few studies have been realized focusing on the management of manufacturing factories as net energy zero systems. There is a lack of new intelligent control functionalities within manufacturing companies which needs to be considered. Such functionalities could be developed and implemented within the factory's EMS. They might allow the factory to operate in an autonomous or semiautonomous way by controlling the energy flows efficiently and dynamically without using or limiting the use of the external grid. The operation of the manufacturing process as a net zero energy factory (NZEF) might be a solution for the factory operators who, in five to ten years, will probably not be allowed to feed the network according to the "feed it and forget it" approach.

Such a way of operating the manufacturing companies requires a high degree of flexibility which needs to be identified and/or developed. These new flexibility options might also be offered to the system operator and might result in a new economic income for the factory operators as participants of the energy sharing economy. It has been pointed out in [17] that industrial prosumers might increase their benefits if they increase their independence from the grid. Controlling strategies aiming to maximize the prosumer self-consumption might have a high impact both on the prosumer's system and the electric grid [18]. An enhancement of the benefits of the control strategies for industrial prosumers proposed can be expected if these strategies also include appropriate storage design.

Energy storage systems and production buffer stocks can contribute to improving the supply and demand matching [19, 20], depending on the technology used [21] and the degree of flexibility of the production processes [22–24]. They enable the system to provide contingency production for load response to energy volatility and move over the production of energy to fulfill production goals. These lead to an increase in the use of on-site generation and the autonomy of the system.

Differently from the scientific contributions mentioned above, the focus of this study lies in not only developing controlling algorithms for operating the system in an optimal way, but also sizing flexibility options within a NZEF concept. Both energy storage systems and production buffer stock are considered as options for matching the volatile power generation of RES. Sensitivity analyses are performed for evaluating how the storage capacities influence the integration of volatile RES into the manufacturing process. The study will, therefore, focus on highlighting solutions to optimally use the energy resources which could be adopted by many factory operators over the next five to ten years when their actual permission to feed the network will have expired or changed.

The study is organized as follows: An overview of a NZEF is given in Section 2. Section 3 develops the methodology, including mathematical model formulation. Section 4 presents the results obtained from the application of the NZEF framework proposed in the case study. The conclusions and future directions are given in Section 5.

2. Net Zero Energy Factory and Methodology of Investigation

Net zero energy systems depict systems in which the electric load is totally or partially covered by generators installed within the system. They might be isolated active distribution networks [25], buildings [26–28], industrial parks or small communities, such as villages [29]. Even if there is no unique definition, only the technologies based on volatile RES are generally referred to as power generators. The time horizon for the net zero approach is not uniquely defined. A system might be net zero for a short or long time. Daily or weekly time horizons are generally considered for small systems, such as houses or buildings. A seasonal or yearly time horizon might be considered for larger systems, such as factories or villages [30]. The electricity generated has to be balanced by the loads consumed (electric and thermal) in the time horizon considered. The thermal load is usually considered in the energy balance when it is generated through electrically driven heat systems, such as heat pumps.

A net zero energy system might be an interesting option for the integration of volatile RES if it can balance the locally generated electricity by limiting the use of the electric grid to which it is connected. In order to do that, the net zero energy system has to be flexible enough to match the volatile generation of RES. The flexibility options within the system need, therefore, to be identified and developed. A NZEF is looked at in detail in this study. A characteristic of the NZEF considered is that the electric loads due to the manufacturing process are controlled to match the power generation of a photovoltaic (PV) plant. In addition, other flexibility options are considered to increase the integration of the electric power generated into the manufacturing process. Energy storage systems (batteries) and production buffer stocks are considered as additional flexibility options.

The aim of the study is, therefore, to analyze how a manufacturing prosumer might be net zero and how the flexibility options should be planned and designed. In order to achieve these aims, controlling algorithms have been developed and both the electric energy storage system and the production buffer stock have been sized. In addition, sensitivity analyses need to be performed to evaluate how the sizes of the storage systems (for the electric energy and the production items) influence the system self-consumption index (SSCI) and the system self-sufficiency index (SSSI). By considering a volatile RES-based generation (i.e. PV plant), the SSCI depicts the ratio between the part of electricity generated, which is directly integrated into the industrial processes, and the total electricity generated. On the other hand, the SSSI depicts the ratio between the part of electricity generated, which is directly integrated into the industrial processes, and the total electricity demanded by the industrial processes [31].

Figure 1 shows the methodology adopted. In the first step, the manufacturing system is analyzed. A mathematical model describing the electricity consumption of the manufacturing system is created. At the same time, models which allow the evaluation of the degree of flexibility of the manufacturing system and the power generated by a PV plant are performed. In the second step, controlling algorithms based on mixed-integer linear programming (MILP) are developed for optimal control of the manufacturing processes according to the power generated by the PV plant. The SSCI (see Eq. (1)) and the SSSI (Eq. (2)) are evaluated for estimating the amount of power generated by PV integrated into the manufacturing process [29],

$$SSCI = \frac{\int_{t_k}^{t_{k+1}} \min\left\{L^t, P_{\mathrm{pv}}^t\right\} dt}{\int_{t_k}^{t_{k+1}} P_{\mathrm{pv}}^t dt}, \tag{1}$$

$$SSSI = \frac{\int_{t_k}^{t_{k+1}} \min\left\{L^t, P_{\mathrm{pv}}^t\right\} dt}{\int_{t_k}^{t_{k+1}} L^t dt}, \tag{2}$$

where L^t is the system power demand in time t, and P_{pv}^t is the power produced by the PV plant.

In the third step, the electric energy storage system and the production buffer stock are sized to increase the degree of flexibility of the manufacturing process. The fourth step aims at performing sensitivity analyses to determine which added flexibility option (electric energy storage or production buffer stock) influences the degree of flexibility of the NZEF most.

3. Methodology Development

This section aims to explain the methodology developed for identifying and modelling the flexibility options within a NZEF. For the sake of simplicity, a case study has been considered and the methodology is explained step by step by using the case study data.

3.1. Flexibility Identification in the Manufacturing Process: Case Study

The performance of the methodology developed for NZEF (see Section 2) has been assessed in a case study representing a manufacturing process. The system consists of semifinished hollow

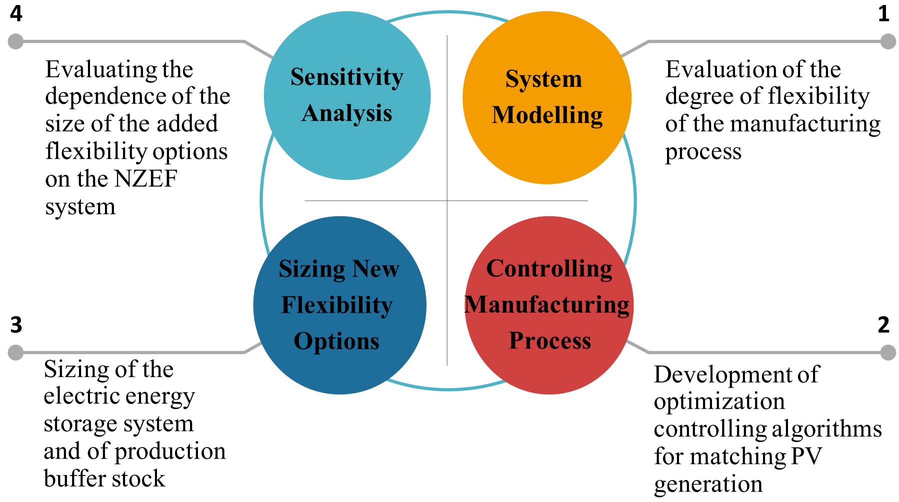

Figure 1: Steps for the proposed framework to design the autonomous industrial prosumer.

cylindrical-shaped work pieces moving through turning, milling and grinding processes in that order. Each process is controlled independently. Each process operates in three modes: Production, idle and off. During the production mode, the process performs work on the pieces. During the idle mode, the process performs no work and consumes low power. During the off mode, the process does not consume power. Intermediate conveyor belts move workpieces between processes.

The cycle time of all conveyor belts can be controlled continuously. All conveyors have the same cycle times and power demand. Intermediate buffers are located after every process and at every conveyor belt. Intermediate buffers support power load flexibility by storing and supplying workpieces while some processes are temporarily in the idle or off mode. Production buffer stock maximal capacity $Cp^{i}_{\max}$ should be designed to fulfill the power demand flexibility and production requirements of the process. The production buffer stock minimal inventory $Cp_{\min}$ is set to 10 items. The first process has a permanent supply of items.

Each production buffer stock has an initial fill level $x^{i,0}_{\text{buff}}$ of 45 items. The manufacturing system demands a maximal electric power of $L_{nom} = 26.8kW$ in normal operation. This value is used in the following as a reference demand profile. Each process is characterized by the parameters cycle time s, production power demand P_{prod} and idle power demand P_{idle}. Cycle time s is the time the process takes to perform the work on each piece. The P_{prod} and P_{idle} are the process power demand for each mode. The P_{prod} represents the maximum power demand for conveyors. It can also be varied by controlling the conveyor's cycle time.

Parameter values are different for each process. Data and parameters of the process are summarized in Table 1. These data were collected from conventional production industry processes which were presented in [13]. Finished products are withdrawn from the last buffer at an adjustable rate $n_{\text{del}} = 1/s_{\text{del}}$ indicating different customer demand. The customer cycle determines item production requirements for the period simulated. The customer cycle time for the case study is set at $s_{\mathrm{del}} = 700[s]$. Variable δ_{del} controls the customer cycle. Then, $\delta_{\mathrm{del}} = 1$ for continuous production. In addition to the manufacturing process, the system generated electricity on-site by using a PV plant. On-site generation supply P^t_{pv} is modelled by the use of historical data

Table 1: Case study parameters

	Parameter		
Process	s [s]	P_{prod}[kW]	P_{idle} [kW]
Turning	263	4	2.5
Milling	206	5.3	4
Grinding	223	13	9.3
Conveyor	20	1.5	-

collected for one-year solar radiation for Magdeburg, Germany (latitude 52.12773, longitude 11.62916). Sample time is 15 minutes and the PV installed power capacity is $P^{\mathrm{nom}}_{\mathrm{pv}} = 49.5\ kW$. Figure 2 shows the yearly generation curve. A down sample technique [32] is used to aggregate data for one-hour time slots for computational purposes in long-term scenarios. The system also includes an energy storage system with nominal power P_{stge} and storage capacity C_{stge} whose values depend on the flexibility requirements, and load profile.

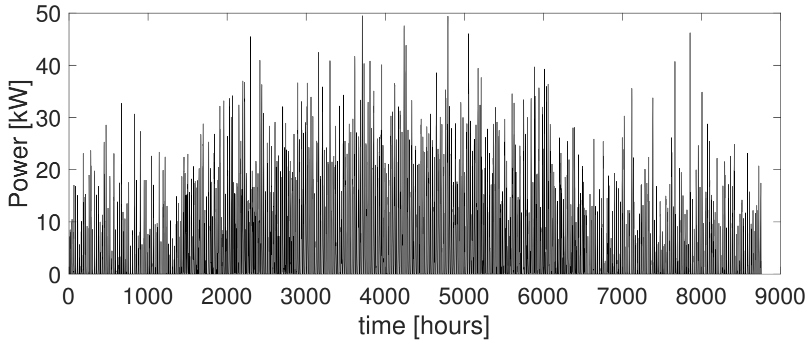

Figure 2: Yearly power generation profile for the $49.5kW$ photovoltaic (PV) plant.

3.2. System Modelling

The manufacturing system model proposed in this work is based on the model presented in [13]. It generates valuable information about production, management, design and control. The model includes the interrelation between production component level characteristics (e.g. cycle time, process modes, production buffer stock capacities) and system level characteristics, such as production rate, processes control and power demand. In addition, the energy storage system is included in the model.

3.2.1. Component level characteristics

The manufacturing system model consists of N processes, each denoted by S^i, and N intermediate production buffers B^i, connected in series as is shown in Figure 3. Index i numbers the processes and the buffers.

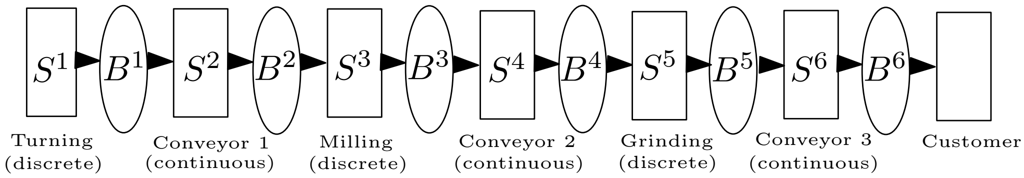

Figure 3: Simple manufacturing system model.

Each process accomplishes product conversion, or transport, in a given processing cycle time $s^{i,t}$ where t is the simulation time and $n^{i,t} = 1/s^{i,t}$ its production rate. The cycle time represents the time required by a process to work on an item. Two types of processes are considered in the model: Discrete and continuous. Discrete processes perform product-related work on items, while continuous processes transfer items between production processes. Regarding nomenclature, variables associated with continuous processes are distinguished by the subindex C and those with discrete processes by subindex D.

Discrete processes S^i_{D} handle three operation modes: Production, idle and off. Binary variables $\delta^{i,t}_{\mathrm{prod}}$ and $\delta^{i,t}_{\mathrm{idle}}$ control the production and idle mode, respectively, and off mode is equivalent to $\delta^{i,t}_{\mathrm{idle}} = \delta^{i,t}_{\mathrm{prod}} = 0$. Continuous processes S^i_{C} operate in a controllable mode where cycle time $s^{i,t}_{\mathrm{C}}$ can be changed according to the requirements of the system.

Production buffer stocks B^i store work in progress products for all the stages of the manufacturing system. Production buffer stocks are modelled as "first in first out" (FIFO) queues with maximum storage capacity denoted by $Cp^i_{\max}$ and cumulative fill level by $x^{i,t}_{\mathrm{buff}}$. Cumulative fill level dynamics can be modeled for all buffers, as shown in Eq. (3).

$$x^{i,t}_{\mathrm{buff}} = x^{i,t-1}_{\mathrm{buff}} + \left(1/s^{i,t} - 1/s^{i+1,t}\right)T, \tag{3}$$

where T is the time slot length. The cumulative fill level $x^{i,t}_{\mathrm{buff}}$ changes according to the cycle times of previous and posterior processes. Buffer stock then depends on its actual condition, how fast the items move between processes and how much elements produce during each process at each time slot T.

In addition, a rule based on the average system throughput is used to limit the control actions regarding bottleneck processes that can block or starve other operations and production (see Eq. (4)).

$$1/N_{\mathrm{D}} \sum_i x^{i,t}_{\mathrm{buff,D}} \leq x^{j,t}_{\mathrm{buff,D}} \qquad \text{for all} \quad j \tag{4}$$

Consequently, processes whose current buffer fill level within the planning horizon is less than the average current buffer fill of all other process levels cannot be switched off or left idle. Consequently, if a process has a lower rate of production, it will keep active to maintain a constant output.

Additionally, the production buffer fill level is controlled to evade process starvation by maintaining a minimal inventory $Cp_{\min}$ for all the processes (see Eq. (5)).

$$Cp_{\min} \leq x^{i,t}_{\mathrm{buff}} \leq Cp^i_{\max}. \tag{5}$$

The model aims at keeping throughput constant with s^t_{del} constant. The temporarily switched off or idle process mode depends on the system power requirements, buffer capacity and bottleneck conditions.

3.2.2. System level characteristics

The power demand of the manufacturing process depends on the state of the process. The model is defined similar to that presented in [13] comprising three discrete processes (turning, milling and grinding) and three equal continuous processes (transport). Power demand is fixed for each discrete process and depends on the operation mode. Idle mode requires a fixed power amount $P^i_{\mathrm{D,idle}}$. The process performs work in the production state at instant t at a specified rate $n^{i,t}$ requiring a superior power quantity $P^i_{\mathrm{D,prod}}$ for production. When the process is switched off, there is no consumption, $P^i_{\mathrm{off}} = 0$. The model neglects time to transition between idle and production. The power demand for continuous processes $P^j_{\mathrm{C,prod}}$ changes by scaling flexible production rate changes linearly.

The power demand L^t of the manufacturing system shown in Figure 3 during time slot t is evaluated according to Eq. (6)

$$L^t = L^t_{\mathrm{D}} + L^t_{\mathrm{C}}, \tag{6}$$

where L^t_{D} is the sum of discrete process demands and L^t_{C} the sum of the continuous process power demands.

The idling mode for discrete processes is controlled by the Boolean variable $\delta^{i,t}_{\mathrm{idle}}$ and requires a fixed power demand $P^i_{\mathrm{D,idle}}$. The production mode is controlled by the Boolean variable $\delta^{i,t}_{\mathrm{prod}}$ and requires a fixed maximum power consumption $P^i_{\mathrm{D,prod}}$. The server can be in the off mode (i.e. $\delta^{i,t}_{\mathrm{idle}} = \delta^{i,t}_{\mathrm{prod}} = 0$, with $P^i_{\mathrm{D,off}} = 0$). Utilizing this, discrete process demand is estimated according to Eq. (7)

$$L^t_{\mathrm{D}} = \sum_i^{N_{\mathrm{D}}} \left(\delta^{i,t}_{\mathrm{prod}} P^i_{\mathrm{D,prod}} + \delta^{i,t}_{\mathrm{idle}} P^i_{\mathrm{D,idle}}\right), \tag{7}$$

and constrained as explained in Eq. (8)

$$\delta^{i,t}_{\mathrm{prod}} + \delta^{i,t}_{\mathrm{idle}} \leq 1, \qquad \delta^{i,t}_{\mathrm{prod}}, \delta^{i,t}_{\mathrm{idle}} \in \{0, 1\}\,. \tag{8}$$

Eq. (8) makes sure that each process can be in only one state at each time slot. Continuous process power demand $L^{j,t}_{\mathrm{C}}$ defined by Eq. (9) has a power consumption proportional to its variable production rate with a maximum power consumption $P^j_{\mathrm{C,max}}$. Total continuous load L^t_{C} is defined as

$$L^t_{\mathrm{C}} = \sum_j^{N_{\mathrm{C}}} P^{j,t}_{\mathrm{C}}, \tag{9}$$

and $P^{j,t}_{\mathrm{C}} \propto n^{j,t}_{\mathrm{C}}$ is proportional to the production rate. The state of Eq. (8) and (9) will control the value of the variable cycle times in Eq. (3).

3.2.3. *Energy storage system*

The model includes an energy storage system with variables P^t_{soc} as the State of Charge (SoC) at time t, P^t_{ch}, and P^t_{dch} representing storage charge and discharge at time slot t, respectively. The P_{stge} is the storage nominal power. The energy storage system's constraints for charging/discharging power limits and SoC should be considered. The charging and discharging power constraints are described by Eq. (10) and (11), respectively. These constraints refer to the upper and lower power limitations for the charging and discharging process. Boolean variables for charging state δ^t_{ch} and discharging state δ^t_{dch} control the storage dynamics. Constraint in Eq. (12) guarantees that the battery will not be in both states at the same time.

The SoC dynamic is described by Eq. (13). This dynamic describes the SoC condition of the storage system including efficiency. For the purpose of this study, the AC - DC efficiency has been considered as $\eta_{\text{ch}} = \eta_{\text{dch}} = 0.9$. Eq. (14) includes constraints for the depth of discharge $E_{\min} = 0.2P_{\text{stge}}$ and maximum charge for the storage system $E_{\max} = 0.8P_{\text{stge}}$. The discharge time h is the maximum duration for which the system can discharge the rated power. The energy storage capacity C_{stge}, is defined in tems of the discharge time h (see Eq. (15)).

$$0 \le P^t_{\text{ch}} \le \delta^t_{\text{ch}} \cdot P_{\text{stge}}, \tag{10}$$

$$0 \le P^t_{\text{dch}} \le \delta^t_{\text{dch}} \cdot P_{\text{stge}}, \tag{11}$$

$$\delta^t_{\text{ch}} + \delta^t_{\text{dch}} = 1, \qquad \delta^t_{\text{ch}}, \delta^t_{\text{dch}} \in \{0, 1\} \tag{12}$$

$$P^t_{\text{soc}} = P^{t-1}_{\text{soc}} + \eta^m_{\text{ch}} P^t_{\text{ch}} - \frac{1}{\eta_{\text{dch}}} P^t_{\text{dch}}, \tag{13}$$

$$E_{\min} \le P^t_{\text{soc}} \le E_{\max}, \tag{14}$$

$$P_{\text{stge}} \cdot h = C_{\text{stge}}. \tag{15}$$

3.3. *Controlling the Manufacturing Process*

In order to have a NZEF, controlling algorithms need to be implemented and integrated into the factory's EMS. The controlling algorithms have to be able to maximize the matching between the electric power due to the manufacturing processes and the electric power generated by the PV plant.

The optimization control for the power demand considers the process modelled and calculated in Section 3.2. It is assumed at the beginning of each controlling period that a known measure or estimation of the power profile supplied by the PV plant exists. The process control is carried out depending on two parameters associated with the system: A demand benefit factor (ξ) that assigns the importance weight to the supply/demand matching and the normalized PV plant power p^t_{pv} defined by

$$p^t_{\text{pv}} = P^t_{\text{pv}} / P^{\text{nom}}_{\text{pv}}. \tag{16}$$

The power demanded by the process must clearly be enough to guarantee continuous production $\delta^t_{\text{del}} = 1$, where δ^t_{del} is the mode of continuous production for the manufacturing process. Control is calculated for two types of NZEF configuration:

- Flexible demand control: Manufacturing processes can be switched between production, idle and off modes at different times in the year depending on the PV power forecast and the production expected. Demand can be shifted in a given period, but the amount of energy to be consumed for each process is known and established previously. Power from the grid is used to achieve power/supply balance.

  Formulation 1: Maximize the matching between on-site generation and power demand while maintaining a fix production rate.

$$Maximize \qquad \sum_t \xi p^t_{\text{pv}} L^t$$

$$s.t. \qquad L^t - P^t_{\text{pv}} - \Delta P^t_{\text{grid}} = 0 \tag{17}$$

$$\delta^t_{\text{del}} = 1, \qquad \delta^t_{\text{del}} \in \{0, 1\} \tag{18}$$

$$Eq.\ (3)\text{-}(9)$$

Eq. (17) represents the balance between power demand, on-site generation P^t_{pv} and power grid contribution ΔP^t_{grid}.

The objective function represents the total benefit over the optimization horizon considering on-site generation availability. The decision variables for the model are the total power demand L^t and the grid power consumption ΔP^t_{grid}. Auxiliary variables include all those displayed in the model (see Eqs. (3) - (9)). The benefit obtained from PV power use is directly proportional to its availability for t. Consequently, the scheduling supports energy consumption at higher peak PV plant production hours during the day. Figure 4 presents the open-loop control obtained by solving *Formulation 1*. Results of this approach are used as inputs for the storage sizing process.

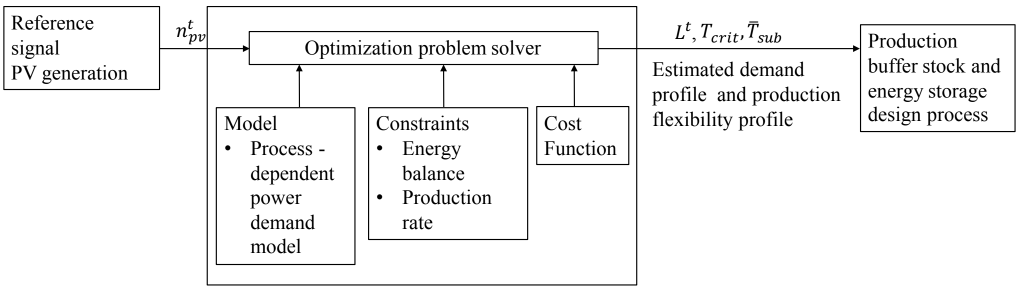

Figure 4: Control obtained by solving Formulation 1.

- Flexible demand control including energy storage: The manufacturing system demand is controlled depending on the PV power forecast and the production expected. The energy storage system is scheduled along a given period to achieve a power/supply balance. The design of energy storage and production buffer stocks obtained following the principles depicted in Section 3.4 are used for parameters in this configuration.

  Formulation 2: Maximize the matching between on-site generation and power demand while maintaining a fixed production rate and reducing the use of energy storage.

$$Maximize \qquad \sum_t \left(\xi p^t_{\mathrm{pv}} L^t - c_{\mathrm{dch}} P^t_{\mathrm{dch}}\right)$$

$$s.t. \qquad L^t + P^t_{\mathrm{ch}} - P^{\mathrm{t}}_{\mathrm{dch}} = P^t_{\mathrm{pv}} + \Delta P^t_{\mathrm{grid}} \tag{19}$$

$$\delta^t_{\mathrm{del}} = 1, \qquad \delta^t_{\mathrm{del}} \in \{0, 1\} \tag{20}$$

$$Eq.\ (3)\text{-}(15)$$

Formulation 2 includes the energy storage designed for autonomous behavior. The decision variables for the model are the total power demand L^t, the grid power consumption ΔP^t_{grid}, the energy storage discharge power P^t_{dch} and the energy storage charge power P^t_{ch}. Auxiliary variables include all those displayed in the model (see Eqs. (3) - (15)). The objective function includes a penalization for storage use defined as the cost of discharge c_{dch}. The balance constraints in Eq. (19) also include the storage charge P^t_{ch} and discharge P^t_{dch} in the balance. The constraint showed in Eq. (20) defines a constant production delivery rate. It implies that demand and storage response are constrained to maintain a minimum production fixed delivery rate n_{del}. No loss of production is permitted in the scheduling. The mathematical model of the manufacturing process, power demand and storage is also included by Eqs. (3) - (15). Figure 5 summarizes the control strategy of the NZEF. The input of the control is the PV power production data forecasted. The control solves the optimization problem in *Formulation 2* and returns the control signals for the manufacturing system.

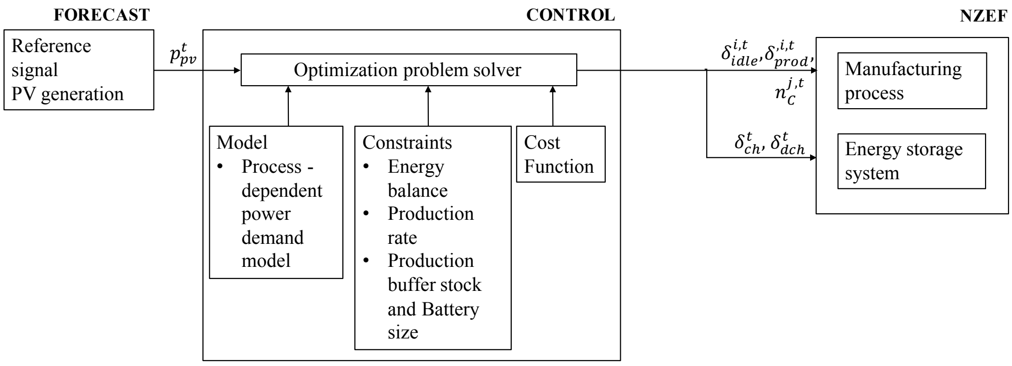

Figure 5: Block diagram for the open-loop control strategy.

3.4. *Sizing New Flexibility Options*

Results from the optimization problem in *Formulation 1* are used in this section to design the energy and production storage systems according to the flexibility required for the system. Designed storages will be used in *Formulation 2* to obtain the NZEF flexible control strategy.

3.4.1. Energy storage sizing

Energy storage sizing is an influential factor for the optimal scheduling of the manufacturing process [33, 34]. In order to use a battery storage system for the NZEF, the system has to be designed by analyzing the battery power and battery capacity requirements and identifying an optimal configuration, considering the production and power constraints available. Battery power P_{stge} can be determined by studying the load profile L^t, obtained from the manufacturing system load control in *Formulation 1* (see Section 3.3) that must be covered by the storage [35]. Consequently, the maximum power for every use is

$$P_{\mathrm{stge}} = \max_t \left| L^t - P^t_{\mathrm{pv}} \right|. \tag{21}$$

Storage capacity C_{stge} is calculated from the total process energy required and the entire time horizon. The capacity is defined as follows

$$C_{\mathrm{stge}} = \max_t \int_t^{t+1} \left(L^t - P^t_{\mathrm{pv}} \right) dt. \tag{22}$$

3.4.2. Setting the size of critical production buffer stock

The methodology used to set the production buffer stock size inspired by [24] is summarized in Figure 6. The strategy includes the following steps:

1. Obtain process optimal scheduling and flexibility time processes. Results of scheduling are power demand, work schedules, production and requirement for buffer inventory.
2. Find the critical bottlenecks concerning production buffer stock. In this case, the production buffer stock associated with the process with the highest potential occurrence of a bottleneck is the critical production buffer stock. This is most commonly considered to be the process with the longest production cycle.
3. Set the size of the critical production buffer stock. In this step, calculate the size of the critical buffer using the maximum flexibility time obtained from the scheduling. Maximum flexibility time $T^{crit}_{\max}$ is the maximum time of the critical process switch to continuous non-production (see Eq. (23)).

   $$Cp^{\mathrm{crit}}_{\max} = T^{\mathrm{crit}}_{\max} \cdot n^{\mathrm{crit}}, \tag{23}$$

   where $Cp^{\mathrm{crit}}_{\max}$ is the maximum size of a critical buffer (items), $T^{\mathrm{crit}}_{\max}$ is the maximum time of flexibility for the bottleneck process (hours) and n^{crit} is the maximum operating capacity of the bottleneck process (items/hour).
4. Setting the size of subcritical production buffer stocks: The size of other production buffer stocks is defined by the average flexibility time of the other processes, as in Eq. (24)

   $$Cp^{\mathrm{sub}}_{\max} = \overline{T^{\mathrm{sub}}} n^{\mathrm{sub}}_{\max}, \tag{24}$$

   where $Cp^{\mathrm{sub}}_{\max}$ is the size of the subcritical production buffer stock, $\overline{T^{\mathrm{sub}}}$ is the average time for the off state of other subcritical processes and $n^{\mathrm{sub}}_{\max}$ is the maximum production rate between subcritical bottlenecks.

This final selection of buffer contributes to evading the process of starving during power demand control.

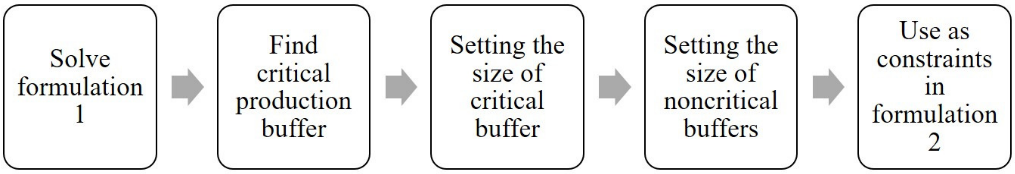

Figure 6: Methodology used to set the production buffer stock size

3.5. Sensitivity Analysis

The final step is a performance evaluation of the NZEF designed. Indices SSCI and SSSI in Eqs. (1) and (2) are defined to evaluate the energetic system performance. As a NZEF indicative, the ratio between self-sufficiency and self-consumption in Eq. (25) should be near to one,

$$\frac{SSCI}{SSSI} = \frac{\int_{t_k}^{t_{k+1}} L^t dt}{\int_{t_k}^{t_{k+1}} P^t_{\text{pv}} dt}. \tag{25}$$

4. Results

In this section, the validity of the methodology proposed is tested by considering a simple NZEF developed to maximize the on-site supply/demand rate. The case study is used for the simulation results.

4.1. Design of Energy Storage Systems and Production Buffer Stocks

The power demand profile and the supply/demand mismatch are obtained by applying *Formulation 1*. Using the solution obtained from the latter, the design of production buffer stocks and energy storage (battery) sizing is made by using methods explained in Section 3.3.

The most critical bottleneck buffer has been identified as the B^1 located after the turning process. This process is considered critical for the bottleneck because it has the longest cycle time. The maximum capacity of critical production buffer stock is sized to $Cp^{\text{crit}}_{\text{max}} = 1781$ items with item inventory for flexibility time $T^{\text{crit}}_{\text{max}} = 130$ hours. Subcritical buffer capacity is sized as $Cp^{\text{sub}}_{\text{max}} = 1500$ items with a capacity of $\overline{T}^{\text{sub}} = 93$ hours production. With the capacities set for buffers, power demand control strategies can be suited. In addition, the design of energy storage gives a storage power and capacity of $P_{\text{ess}} = 68\ kW$ and $C_{\text{ess}} = 6.92\ MWh$, respectively. The parameters designed are used in *Formulation 2* to obtain demand profiles for the case, including the energy storage system. Results are compared in Section 4.2.

4.2. Comparison of Control Strategies

Figure 7 shows the average power demand of the NZEF and the average PV plant power as a function of the time horizon. To guarantee enough production stock for the control, the NZEF is simulated with the initial condition in the high radiation season (e.g. simulation starts in May). Consequently, enough electric energy can be stored which can be used during the low radiation seasons. The time horizon in the simulations varies from May to April of a solar radiation year considered with an eight-hour working day. It starts to generate initial conditions in a high solar radiation season from May. The power average is taken weekly. Results associated with control strategy in *Formulation 1* are described as *control 1*.

Control strategy based on *Formulation 2*, where storage is included, is described as *control 2*. It can be noted that the traditional approach (no control) is unable to exploit a long-term, flexible operation of the manufacturing system. It depends mainly on the assumption that all the machines are switched on simultaneously and they are not controlled at all.

It can be noted that while the traditional approach (no control) is unable to exploit a long-term, flexible operation of the manufacturing system, results for control in both strategy *control 1* and *control 2* increase the energetic efficiency of the process by reducing the demand. Additionally, control strategies improve the PV plant power production steering with a profoundly better performance from the plan, including optimal storage sizing.

Figure 8 shows the power contributions from the grid for each strategy. No control strategy duplicates its requirements if no flexibility options are used, while load control strategies (*control 1* and *control 2*) maintain constant low power grid requirements. Otherwise, *control 2* strategy keeps to minimum requirements compared to strategy *control 1*.

The *control 2* strategy obtains a significant reduction in the PV power excess production. Figure 9 shows the results of the PV plant power excess production. Without control strategy, the system has surplus PV power production which is not used for the manufacturing process during the entire time horizon. This operation mode results in economic and energetic losses for the system. Otherwise, the *control 1* strategy reduces the overgeneration of the PV power, but it continues during half of the time horizon. Different to those cases, the *control 2* strategy achieves zero extra PV power.

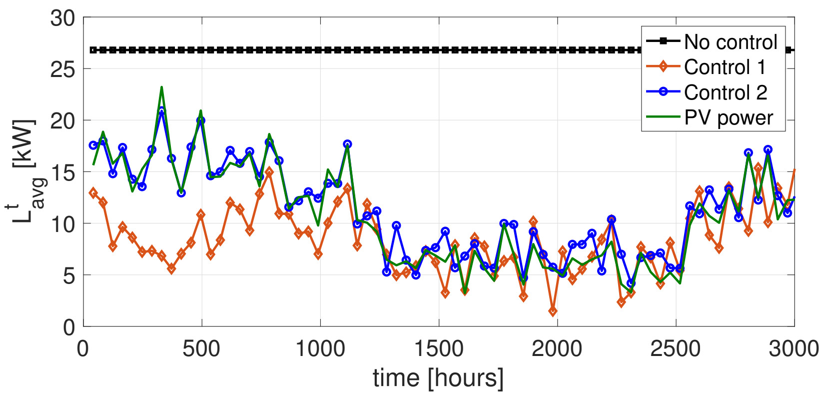

Figure 7: Weekly average power demand for the manufacturing system obtained by control strategies compared with no control load reference and weekly average PV plant power.

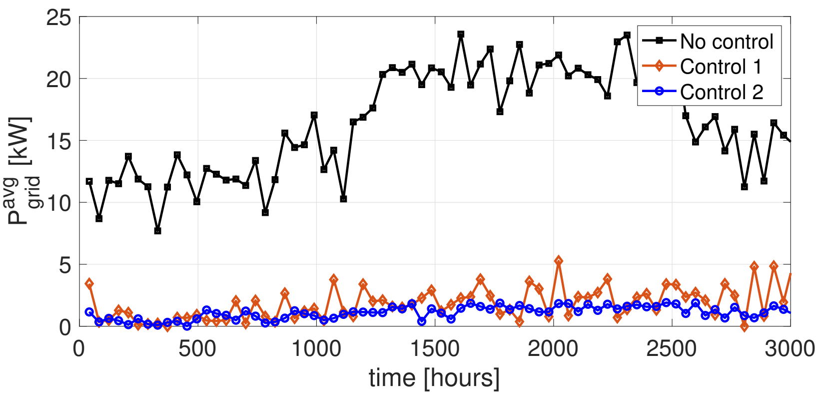

Figure 8: Power used from the grid. Average values are taken over a week

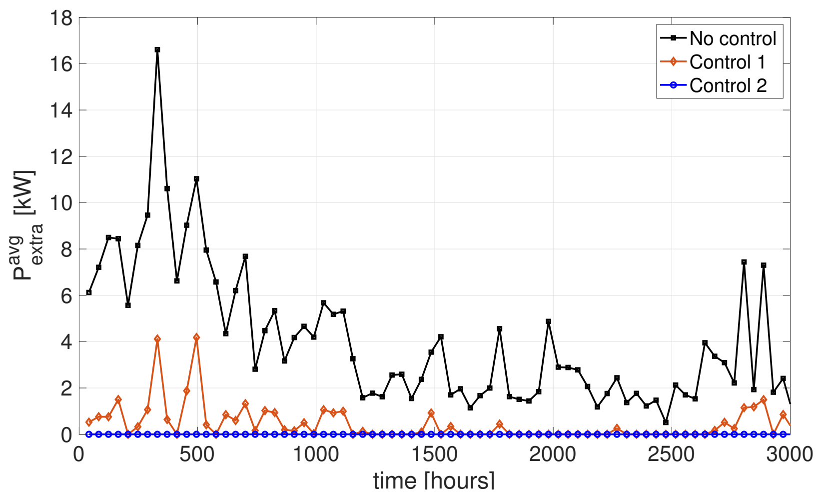

Figure 9: Overproduction of PV plant not used by the NZEF. Average values are taken over a week

Table 2 summarizes the power requirements for the NZEF in different control scenarios with or without energy storage. Three scenarios are considered; Firstly, a time horizon of a year, with no control of the industry load, and variations including and not including storage. Secondly, a time horizon of a year, comparison between control with and without storage. Finally, time horizon seasonal (e.g. excluding low sun radiation months), comparison for control with or without storage. Results show that peak power demand is reduced by the use of control. Yearly power demanded for control plus storage strategies are superior to only control strategy. This difference has an impact on the buffer design. The control plus storage strategy reduces the switching between production and idle in the system. Consequently, fewer semifinished products are stored, and the production buffer fill level is also reduced. Energy storage capacity is significantly reduced by the use of industry load control, improving the energetic efficiency of the system and reducing the PV power over generation loss. Finally, it is possible to observe that the seasonal and year time horizons have no significant difference in energetic benefits for the NZEF.

Table 2: Power and energy demanded

		Time horizon	
		Year	**Seasonal**
no storage	*no control*	*control 1*	
Max. peak power demand [kW]	26.8	24.34	25.3
Yearly(Seasonal) energy demanded [MWh]	29.32	9.7	7.38
Yearly(Seasonal) energy grid used [MWh]	18.1	2.5	1.67
Storage power [kW]	-	-	-
Storage energy [MWh]	-	-	-
Critical production buffers stock [items]	-	unlimited	unlimited
Critical production buffers stock [items]	-	unlimited	unlimited
with storage		*control 2*	
Max. peak power demand [kW]	26.8	24	26.8
Yearly(Seasonal) energy demanded [MWh]	29.32	12.4	8.91
Yearly(Seasonal) energy grid used [MWh]	-	1.2	0.75
Storage power [kW]	42.8	70	68
Storage energy [MWh]	18.6	5.17	4.5
Critical production buffers stock [items]	-	2000	2000
Critical production buffers stock [items]	-	1900	1900

Figure 10 shows parameter requirements in terms of the different time horizon of the NZEF. Total inventory represents the products that are maintained in production buffers to stabilize variations the in manufacturing process control. Total inventory and energy storage capacity could duplicate between year and seasonal time horizons, affecting the costs of this option. Nominal storage power and buffer capacity varies depending on the optimal solution. A middle drop occurs for storage capacity and total inventory data after seven months. Coordination of flexibility options finds its equilibrium for a period of simulation of eight months. The load and storage control assign schedules that minimize the inventory and energy capacity, according to the total energy obtained from the PV power. After eight months inventory and energy storage, the capacity presents a high increase due to the low radiation season.

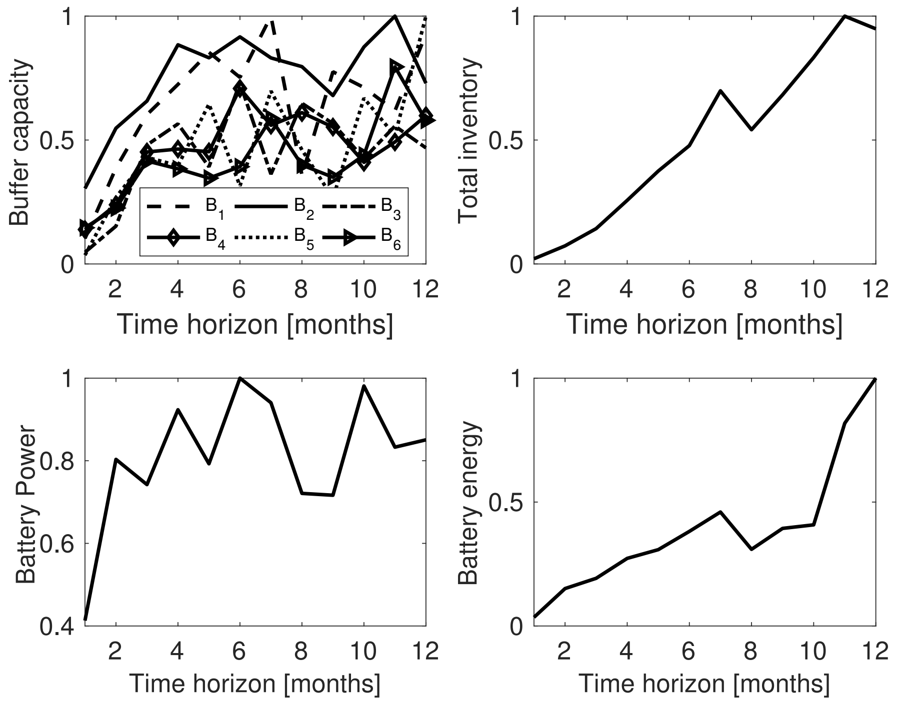

Figure 10: Long-term net zero operation parameter requirements. Signals are normalized according to nominal maximum values for storage power $P_{\text{ess}} = 70kW$, storage energy $E_{\text{ess}} = 7.5MWh$, production critical buffer capacity $Cp_{\max}^{\text{crit}} = 2100$ items and total inventory $2.96e06$ units.

Table 3 shows a summary of the energetic index performance over the time horizon. The control strategy increases the independence of the system by reducing the power demand (increase in SSSI) but decreases the on-site generation consumption (lower SSCI). Strategies using designed storage and control improve the autonomy and energetic performance of the NZEF and have been the best option. No significant difference exists for yearly or seasonal time horizons. Future economic analysis can answer the question about whether seasonal or yearly NZEF is more profitable.

Table 3: NZEF performance

Index	Base case	NZEF control			
		control 1		*control 2*	
		Year	Season	Year	Season
SSCI	0.9579	0.62	0.67	0.80	0.80
SSSI	0. 3831	0.7461	0.77	0.76	0.77
Ratio	0.4	1.19	1.16	1.05	1.04

4.3. Sensitivity of Self-sufficiency to Storage Sizing

Results depend on adequate production buffer stock sizing, which can be shown as follows. Different combinations of critical and subcritical production buffer stock size might be considered to improve the NZEF autonomy under control 1 strategy. By analyzing the performance indexes, the best combination for buffer size results in the pair $Cp_{\max}^{\mathrm{crit}}$ = 2200 items and $C_{\max}^{\mathrm{sub}}$ = 1000 items with a ratio $SSCI/SSSI$ = 1.06 near the unity (see. Figure 11). This value represents a very close match between the energy required by the manufacturing process and the energy produced by the power plant. With such a combination, the SSSI reaches 0.6 (see Figure 12). It means that 60 % of the power demand is covered by the on-site generation. The rest of the on-site generation needs to be fed into the electric grid or stored in a battery. It supplies the NZES during low power generation. Different combinations could be selected depending on what criteria the design supports. A more significant capacity for critical production buffer stock supports the increase in self-consumption by increasing production and inventory. A SSCI of 0.7 (see Figure 13), as in the case of a critical production buffer stock size of 2300 items, guarantees that 70 % of the on-site generation is integrated into the system. Autonomy criteria $SSCI/SSSI$ (Figure 11) is always near to 1.0 using an improved balance between generation and consumption produced by the control actions. The indexes will acquire increased values by using energy storage and power demand control integrated into control 2 architecture.

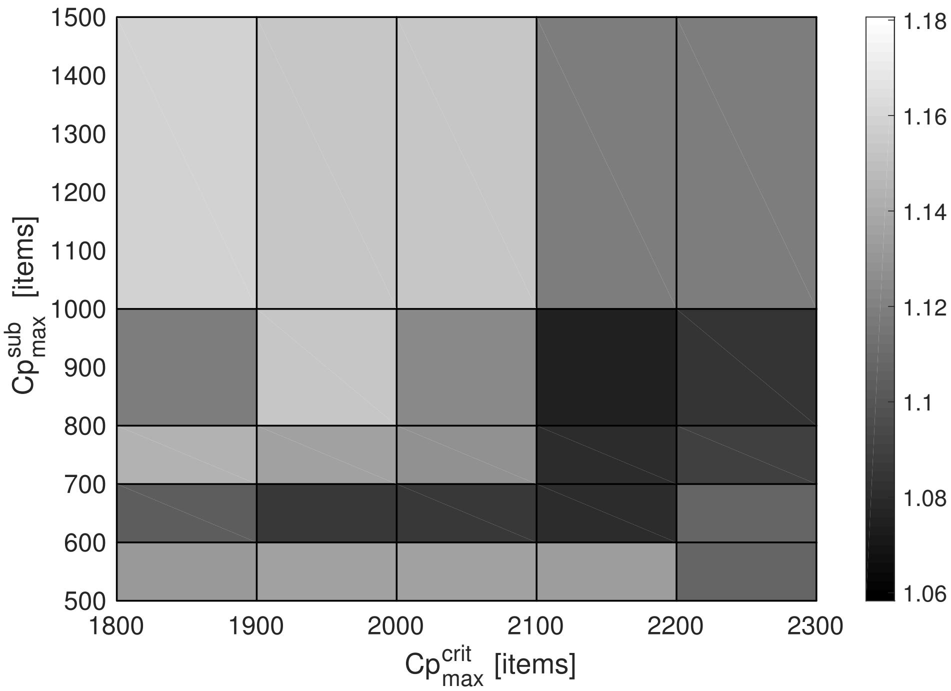

Figure 11: Rate between self-consumption and self-sufficiency is near to 1 for the NZES designed.

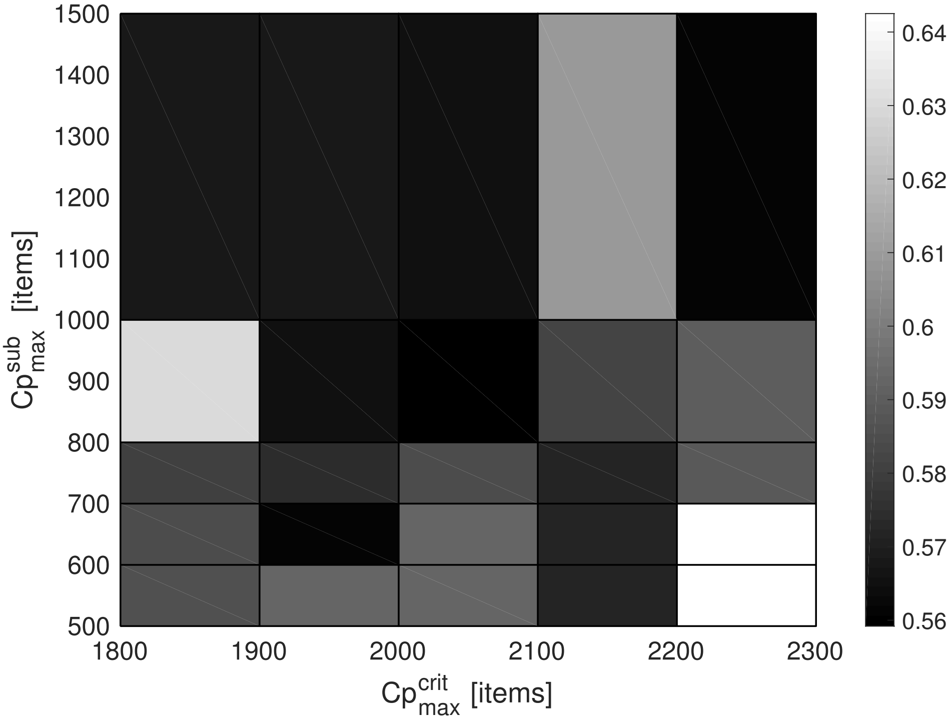

Figure 12: Sensitivity of self-sufficiency index to buffer size variation.

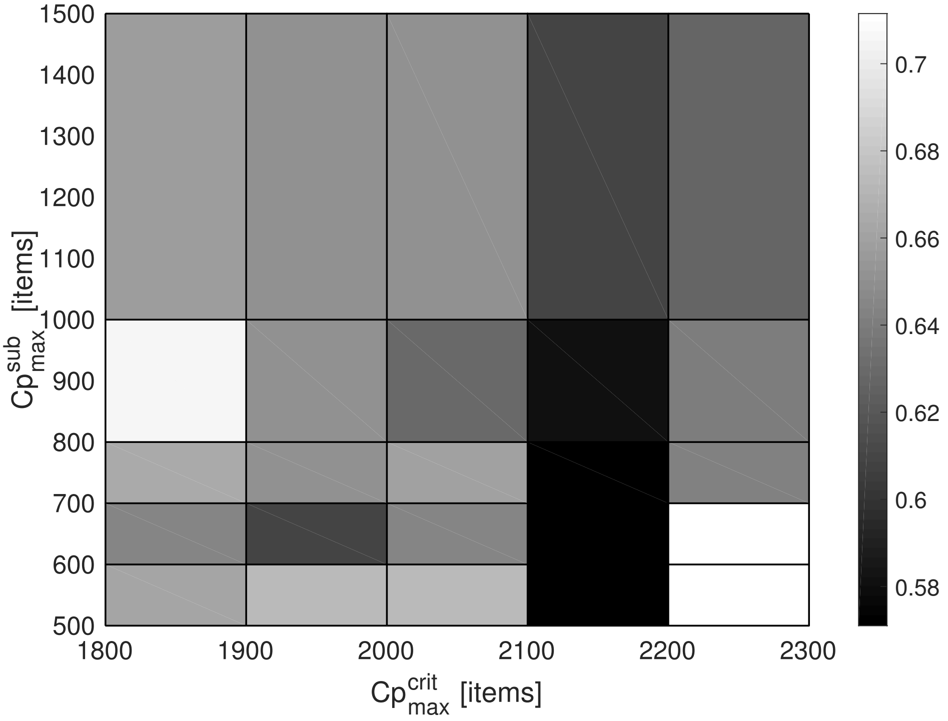

Figure 13: Sensitivity of self-consumption index to buffer size variation.

4.4. Discussion

Optimal scheduling and storage design methodology combine demand control in manufacturing and use of storage improving the penetration of renewable resources in manufacturing processes and producing NZEF behavior. The simulation results of the control proposed show a significant improvement of the NZEF effects by comparison with other scheduling and controls offered in the literature. Even when real-time control of power demand could enhance the flexibility of the system, a full net zero energy operation should be designed including energy storage technologies and an optimal assessment of buffer capacities. The integration of coordinated load control and storage can also reduce the power storage requirements optimally. An important issue to consider in the design of the NZEF is the flexibility and applicability of the system in the long-term planning time horizon. Previous results in literature do not consider weather conditions or cumulated inventories. These parameters result in increased requirements for the development of power demand control strategies. An adequate, economic assessment should be revisited in the future to define whether it is profitable to have a full year grid-independent system, or propose seasonal independency to reduce installed system capacity. The model proposed here can be used for management and planning decision-making by the yearly simulation of forecasted demand profiles of different scenarios and can be easily modified and extended by alternative storage systems and other industrial processes.

5. Conclusions

A methodology was developed for the flexibilization of a NZEF applied to energy generation and manufacturing processes. Based on this, an optimization model for the scheduling and control of power demand in the manufacturing process was implemented. Two optimization algorithms are proposed. The model maximizes matching between on-site power generation and the demand profile. The model achieves the optimization by continuous control and discrete processes in the manufacturing system. The model includes technical restrictions on the operation, storage and energy balance as constraints. Item and energy storage are designed to guarantee the NZEF behavior. Power storage availability and integrated scheduling between load and storage were shown to have a positive impact on the on-site generation and demand matching. However, a trade-off between system efficiency and flexibility could be an obstacle to the implementation of a fully autonomous NZES. Inventory and production buffer stock could increase significantly for long-term flexibility producing an increase in cost by remaining subproduct stocks. Self-sufficiency indices were used to study the sensitivity of the system to buffer and energy storage capacity. The sensitivity of the system to the parameters and time horizon were also assessed. The results obtained in the paper makes the importance of considering an appropriate size-benefit design of item storage explicit and the possibility that a seasonal NZEF operation is more viable than full islanding from the grid. Installing one's own generation capacity could improve performance by the use of scheduled plans for load and storage. Future directions in research aim at multi-objective scheduling optimization of the system, including minimizing the cost of storage capacity and intermediate buffers. The integration of other flexibility options, such as pump heat energy storage, should also be assessed.

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7. Declaration of interest

None.

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