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F. Rossi[a,b], M. Heleno[c], R. Basosi[b,d,e], A. SinicropiV[b,d,e]

[a] University of Florence, Department of Industrial Engineering, Via Santa Marta,3, Florence, Italy. 4
[b] University of Siena, R2ES lab, Department of Biotechnology, Chemistry and Pharmacy, Via A. Moro,2, Siena, Italy. 5
[c] Grid Integration Group, Lawrence Berkeley National Laboratory, Berkeley, Cyclotron Road, 1, CA 94720, USA. 6
[d] CSGI, Center for colloid and surface science, via della Lastruccia 3, 50019, Sesto Fiorentino, Italy. 7
[e] Institute of Chemistry of Organometallic Compounds (CNR-ICCOM), Via Madonna del Piano 10, 50019 Sesto Fiorentino, 8
9 Italy.

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Federico Rossi[a,b,*], Miguel Heleno[c], Riccardo Basosi[b,d,e], Adalgisa Sinicropi[b,d,e]

[a] *University of Florence, Department of Industrial Engineering, Via Santa Marta,3, Florence, Italy.*
[b] *University of Siena, R^2ES lab, Department of Biotechnology, Chemistry and Pharmacy, Via A. Moro,2, Siena, Italy.*
[c] *Grid Integration Group, Lawrence Berkeley National Laboratory, Berkeley, Cyclotron Road, 1, CA 94720, USA.*
[d] *CSGI, Center for colloid and surface science, via della Lastruccia 3, 50019, Sesto Fiorentino, Italy.*
[e] *Institute of Chemistry of Organometallic Compounds (CNR-ICCOM), Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy.*

Abstract

This paper compares the economic and environmental optimal design of Solar Home Systems (SHSs) and explores the role of economic incentives (such as tariffs and technology costs) in approximating the two optima. To achieve that, we present a methodology for the environmental and economic evaluation of grid-connected SHSs: user-scale electric systems involving a photovoltaic (PV) power system and a battery energy storage system. The proposed methodology is based on a mixed integer linear programming (MILP) optimization, life cycle assessment and life cycle costing. This methodological framework is applied to a case study involving a typical SHS installation in Italy. The results of the environmental optimal design brought to the evaluation of a 3.25 kW PV assisted by 8.66 kWh of nickel cobalt manganese batteries, whereas the costs of the SHS are minimized by a small PV system (less than 1 kW). Results underline that the environmental optimal configurations rely on battery technologies, which entails a significant cost compared to the grid connection. In contrast, the economic optimal design solutions is less impactful than the grid mix both from an environmental and economic points of view. Thanks to a reduction of batteries and PV costs, the environmental impact of the economic optimal design is expected to decrease in the future.

Keywords: LCA, LCC, Optimization, Batteries, Solar Energy.

Declarations of interest: none

1. Introduction

This paper is focused on the evaluation of a user-scale electric system, named Solar Home System (SHS), composed of a photovoltaic (PV) system, a battery energy storage system (BESS), a charge controller (CC), an inverter (In) and a backup power source (the grid or a backup generator) [1]. The installation of SHSs are motivated by different objectives, typically the electrification of remote rural areas [2, 3, 4, 5] or the economic gains (self-consumption and feed-in remuneration) in grid connected installations [6, 7]. Besides the economic viability of such installations, the increasing concerns about the environmental problems dealing with the traditional power systems, fueled by fossil fuels, has brought environmental sustainability analyses

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*Corresponding author
Email address: `fe.rossi@unifi.it` (Federico Rossi)

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to be as important as the economic ones [8]. Therefore two SHS optimal configurations are designed in this paper: one minimizing the costs and the other minimizing the environmental impact. This choice comes from the need of comparing the two approaches to evaluate the distance between their results in terms of costs and environmental impacts and to assess which is the economic cost of improving the SHS eco-profile. This comparison is key to support SHS related policies that can generate economic incentives in the direction of environmental optimum. Therefore, this paper explores some of the potentials of theses economic incentives, in particular how the SHS impact results are affected by technologies costs and energy tariffs.

The literature on SHS systems planning and impact is extensive and involves different economic and environmental perspectives. On the economic side, O'Shaughnessy [6] published an interesting review summarizing the results of seventeen SHS economic analyses available in literature, and later proposed their own economic optimal design to size a SHS [9]. Petrollese et al. [10] proposed an Italian case study where optimization is used to maximize the SHS economic benefits associated with self-consumption. Zubi et al. [11] estimated the cost of the energy produced by a SHS, focusing on the contribution of the BESS, whereas Diouf et al. [12] had a broader perspective on the economic benefits related to the adoption of SHSs in some African states. SHSs economic issues have also been addressed by Azimoh et al. [13] with a particular emphasis on role of the installation and use of those systems in mitigating life cycle costs. Ndwali et al. [14] optimized the design of a batteries assisted PV system considering the overall costs of energy and technologies; NREL performed a very detailed analysis on these costs and released a benchmark study [15]. According to this evaluation, batteries have a very important impact on the SHS cost; indeed, NREL estimates the cost of a 5.6 kW PV installation to about 14,000 EUR whereas adding a 6kWh BESS, typical of residential systems, it is about 25,000 EUR [15]. Still in the context of SHS economic analysis, the paper of Cardoso et al. [16] is particularly relevant as the optimal economic configuration of a SHS is defined using mixed integer linear programming (MILP). MILP represents the most widely used approach for power systems optimization because, contrarily to mixed integer non-linear programming (MINLP), its convergence and optimality are guaranteed [16]. Differently from simulation-based optimization, MILP is a mathematical minimization of a cost function that does not involve intermediate results. Other studies, although less abundant, propose the SHS environmental impact estimation. For instance Martinopulos et al. [17] presents a broad overview of economic and environmental impact analyses of electricity production from PV in European context. Nagapurkar and Smith [8] used LCA to evaluate the carbon dioxide emissions of a cost-optimized Microgrid whereas Di Zhang et al. [18] analyzed the environmental impacts of a combined heat and power (CHP) based off-grid system. Recent papers published by Rossi et al. [19, 20] show how the design, modeling and environmental impact assessment of some user scale electric systems based on PV generation, including SHSs, can be connected with each other in a three-steps methodology. The authors concluded that a grid-connected SHS represents the best configuration for the environment.

On the side of the environmental impacts, life cycle assessment (LCA) is particularly useful because it allows to consider all the direct and indirect burdens connected with all the phases of the life cycle of a technology. Indeed it is possible to evaluate the negative and positive effects on the environment of the natural resources consumption and of the direct and indirect emissions occurring during the raw materials extraction, transports, manufacturing, operation and the disposal [21]. Moreover, several environmental impact categories can be investigated including global warming potential, resources depletion, acidification and eutrophication potential and other types of impacts [22]. This represents a remarkable difference with other environmental assessment methods which include only direct carbon dioxide emissions to the environment [23]. This is particularly relevant in the evaluation of technologies, such as PV and BESS, that are not responsible for pollutant emissions in their operation, but have a significant impact during other phases of their life [24]. For all these reasons, the International Organization for Standardization (ISO) decided to define a standard procedure to perform a LCA analysis in ISO 14040 and ISO 14044 regulations [25, 26]. The life cycle approach became so important that it has been extended from the environmental analyses to the economic and social evaluations with Life Cycle Costing (LCC) and social LCA [27]. The tools necessary to perform a LCA analysis are a database, provided by Ecoinvent [28] to collect the information for the model definition, and a computational software, in this case openLCA [29].

In the field of LCA, a particular attention is devoted to the energy storage system (ESS) due to the variety of battery chemistries, materials and technical properties. For instance cobalt is a metal providing high energy density to the battery, but at the same time it is becoming rare and expensive [30]. In order to perform LCA of batteries, the input data have been recovered from Peters et al. [31, 32]. In these papers the main LCA studies based on primary data of the main Lithium-ion batteries (LIBs) commercially available have been gathered and modified to provide a single harmonized database. The same nomenclature adopted by Peters and Weil [32] has been used to address these LIBs: particularly nickel cobalt manganese (NCM), lithium iron phosphates (LFP) [33, 34, 35], nickel cobalt aluminium (NCA), lithium iron titanate (LTO) [36] and lithium manganese oxide (LMO) [37] batteries have been compared. Concerning the costs of these devices, some very detailed and reliable analyses are available in literature [15, 38] and are considered as a reference in this study. Additionally, it was demonstrated that the ageing of ESSs strongly affects the results of optimization during the design and management phases [16] and represents a major concern for economic and environmental problems. For such reason, batteries degradation models [39] are often applied in investments decisions tools [40, 16]. Some of these models are also very specific for SHS applications [1, 19] but usually they aren't involved in SHS design optimization [16]. MILP is a very powerful instrument because it allows, using appropriate assumptions, to include both cyclic and calendar ageing expressions in SHSs optimal design [16].

Despite the rich literature on SHSs, there is a lack of attention to the cross-analysis between economic and environmental optimal designs in different contexts. The methodology presented in this paper is built on Rossi et al. [19, 20] and Cardoso et al. [16] papers. The contributions are threefold:

- An optimization model for optimal environmental design, based on LCA. This model mimics the economic model.

- A comparative cross-analysis between economic and environmental solutions in a realistic case study. This involves evaluating the environmental impacts of the economic optimum and vice-versa; the comparison of the results allows to discuss the costs related to the mitigation of the SHS environmental impact.

- A sensitivity analysis around the cost of technologies and energy tariffs.

The rest of the paper is divided as follows: in Section 2 the innovative approach applied in this paper will be explained and in Section 3 it will be applied to a case study; in Section 4 the results will be illustrated and in Section 5 the conclusions will be presented.

2. Methodology

In this methodological section, the economic and environmental optimization models will be illustrated. First, the cost functions of the problem will be defined, then the mathematical constraints coming from the physical limits of the SHS will be described. Finally, a methodological framework for the comparison of the results provided by the economic and environmental optimization problems will be proposed in order to discuss the economic costs of improving the SHS environmental performances. This evaluation can be very useful to support decisions during the design of a SHS. A high level of detail is used to design this methodology because, although it is based on well known approaches, their integration is proposed for the first time and therefore it can be considered as part of the results of the study as well. A sketch of the methodological framework is illustrated in Figure 1.

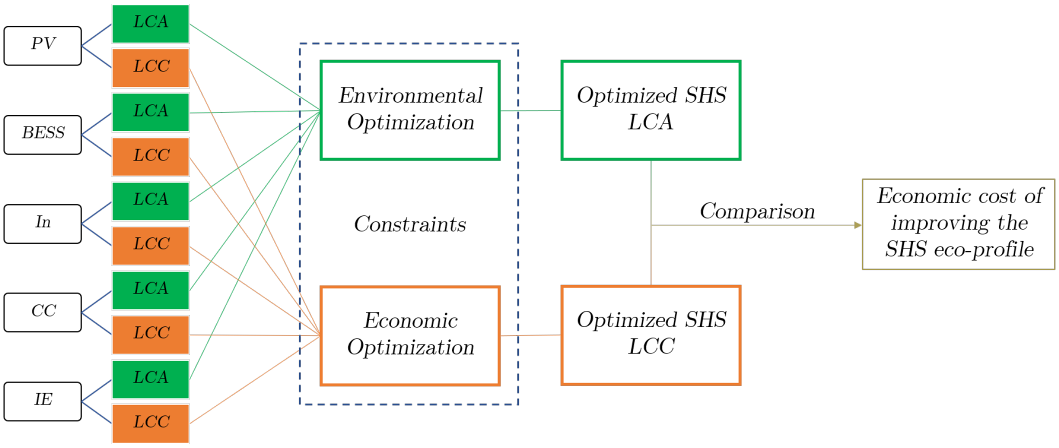

Figure 1: Sketch of the applied methodology.

2.1. Economic Optimal Design

In this section, the economic optimal design of a SHS will be discussed to minimize the costs of private consumers investing for the adoption of a SHS. Consumers decisions will be assumed to be driven only by rationality in the acquisition and utilization of DER technologies. In this section, this rationality is presented as an economic optimal design, where individual consumers size their SHS and dispatch energy to minimize the costs. The economic optimal design model proposed by Cardoso et al. [16] and included in the overall modeling framework of the Distributed Energy Resources Customer Adoption Model (DER-CAM) tool [41], has been adopted as a reference for this study. This model considers all the annualized expenses that a user should afford in case its energy consumption is guaranteed by a grid-connected SHS. According to ISO 15686 [42] standard for LCC, these expenses are distributed over the SHS lifespan: the cost of technologies includes several contributions like the construction, the supply chain, the marketing and the disposal. Furthermore, during the operation of the SHS, the user might import and export energy from the grid, which implies costs and revenues for the user. In other terms, an optimized LCC is performed grounding on Cardoso et al. [16] model. As common practice in LCA and LCC, the results are referred to a Reference Flow (RF). As the function of the SHS is providing electricity to the user, the RF is defined as the amount of electricity provided to the load (Eq. 1).

$$RF = \sum_{t \in \tau_{yr}} \left(\frac{Ld_t}{1000} \right) \tag{1}$$

Where, Ld_t is the power absorption of the user hour by hour, whereas τ_{yr} is the set of hourly time points over one year. The cost function (2) takes into account the costs of technologies (defined by the subscript k). These costs are classified as fixed ($CFix_k$), that don't depend on the components capacity (cap_k), and variable ($CVar_k$) that depend on the capacity. Furthermore, the tariffs are also taken into account: the hourly costs (EC_t) of the electricity withdrawn from the grid (ui_t) and the remuneration paid by the utility (FI_t) for the energy injected into the grid (ue_t) are required. All these costs must be annualized and represent input parameters of the economic optimal design. The variable i_k is a binary variable discriminating the technologies which are adopted and those that are not. The overall SHS life cycle cost per MWh of energy supplied to the user (C) is calculated by the economic cost function (2):

$$C = \frac{\sum_{k \in \{SHS\}} \Big(CFix_k \cdot i_k + CVar_k \cdot cap_k \Big) Ann_k + \sum_{t \in \tau_{yr}} (ui_t \cdot EC_t - ue_t \cdot FI_t)}{RF} \tag{2}$$

Where τ_{yr} is the set of hourly time points over a year and the factor Ann_k is calculated defining an interest rate (ir) of 3% using Eq. (3) [43] and setting the lifespan of the components (L_k):

$$Ann_k = \frac{ir}{1 - \big(1 + ir\big)^{L_k}} \tag{3}$$

2.2. Environmental Optimal Design

Economic analyses of renewable energy technologies aim to improve their economic competitiveness compared to traditional energy systems using fossil fuels. Several environmental problems, such as climate changes and desertification, are attributable to greenhouse gases emissions due to the combustion of fossils.

For such reason some consumers are also starting to follow a rationality driven by the environmental sustainability. Indeed, in this section we propose an optimization model equivalent to the one described in the previous section where the environmentalist rationality is considered as the only criterion for the SHS design and management. An environmental cost function, derived from the economic optimization, minimizing the environmental impact of SHSs is defined. Differently from the economic side, an optimized LCA based on a MILP does not exist so far and is developed in this study. Indeed the big novelty compared to DER-CAM environmental optimization [23], which is based on direct carbon dioxide emissions, is that LCA allows to evaluate more environmental impact categories: all the direct and indirect environmental burdens, including raw materials consumption, over the SHS life cycle can be accounted for. The parameters involved in the environmental optimization problem are calculated through a LCA. According to ISO 14040 and ISO 14044 standards, LCA is composed of 4 steps [25]:

- *Goal and Scope definition*: the aim of the analysis is described including the definition of the system boundaries, the function of the system, the RF and the functional unit (FU).
- *Life Cycle Inventory (LCI)*: all the input and output flows of matter and energy involved in the system boundaries during the system lifespan are considered and quantified;
- *Life Cycle Impact Assessment (LCIA)*: the environmental impacts are calculated using standard assessment methods converting the amounts of energy and matter defined in the LCI phase to impact values;
- *Interpretation*: the LCA analyst should evaluate the results of the LCIA and all the previous steps of the analysis in order to adapt and modify the LCA model if necessary.

From a methodological point of view, LCA is equivalent to LCC as it is useful to assess the environmental impacts of a product, a system or an industrial process during their life cycle.

The function of the SHS is to provide electricity to the load and thus the RF, defined as the main output, is the amount of energy supplied to the user (1). The FU, set to 1 MWh, must be coherent with the RF but it doesn't depend on its amount; indeed it is a quantity used to make the SHS comparable with other product systems having the same function: for instance expressing the SHS environmental impacts per MWh of energy provided to the user allows the comparison with 1 MWh of energy from the electricity mix. The LCA analysis is performed using the software openLCA [29] and the database Ecoinvent 3.4 [28] that allows to define the inputs and the outputs of a SHS, named Flows, represented in this case by the SHS components and energy flows. The production, the installation, the disposal and all the other operations involved in the Flows life cycle are named Processes and are also contained in the database. As any LCA software, openLCA evaluates the LCI of the SHS summarizing all the Elementary Flows (the liquid, gaseous or solid emissions to the environment and the raw materials) involved in the SHS life cycle. LCIA calculation methods multiply the Elementary Flows by impact factors and then sum the results to get an environmental impact value. As 1 MWh of energy to the load is set as FU of the study, the results must be divided by the RF.

The same result evaluated with this classical approach, could be obtained changing the order of the LCIA steps as following. For each Flow of the SHS, the unitary environmental impacts of the components and of energy are calculated, which means evaluating the burden of a 1 kW In, 1 kW CC, 1kWh BESS, 1 kW PV system and 1 kWh of electricity imported from the grid. After that, all the unitary impacts are multiplied by the respective Flow Quantity. In the end, the sum of these products is divided by the RF to respect the functional unit of the system. If the Quantities (cap_k) are not considered as inputs but as variables of this problem, this formulation of the LCIA can be seen as a cost function whose minimization provides the minimum SHS environmental impact and the optimal capacity of the PV system (cap_{pv}), of the the BESS (cap_s), of the CC (cap_{cc}) and of the In (cap_{in}). The unitary environmental impacts are the optimization problem parameters. Nevertheless some adaptations are necessary to make these two equations equivalent and consequently comparable.

First, the unitary environmental impacts must be classified as variable impacts ($IVar_k$), which depend on the Quantity, and fixed impacts ($IFix_k$), which don't depend on the Quantity.
Moreover, in order to be coherent with Eq. (2), the life cycle impacts of the SHS Flows must be annualized. Whereas the economic costs of technologies are annualized by Eq. (3) considering an interest rate, to obtain annualized environmental costs of technologies it is enough to divide the impacts by the components lifespan (L_k). In this way, the longer is the components lifespan, the lower is their annualized impact.
As the SHS is supposed to be connected to the grid, the system can inject exported energy (EE) and use imported energy (IE) from it. The economic optimization problem includes the evaluation of some revenues coming from the electricity exportation to the grid. In LCA, the evaluation of the by-products is not always necessary, but two different methods exist: system expansion and allocation [44] which are of difficult use in our case. Indeed using the system expansion is equivalent to set some environmental revenues because the exported electricity can be defined as an output flow that allows to avoid the production of the same amount of electricity from the mix, whose impact is consequently subtracted to the total. Nevertheless in this case the system expansion would lead to unrealistic results because the size of the PV system would be out of the range of residential applications and the SHS would lead to a very big negative environmental impact. For such reason allocation has been preferred by Rossi et al. [19, 20] to describe this multi-output process: using this approach, part of the impacts are allocated on the RF, and part of them on the by-product. Physical allocation is one of the most widely used allocation methods and consists on multiplying the impacts for an allocation factor, calculated as $RF/(RF + EE)$. The allocation factor has in the denominator the exported electricity which is an optimization variable: consequently the cost function would become non-linear. Non-linear problems are more complex to be solved than linear and their convergence is not guaranteed. The same issue exists if other types of allocation are chosen; for instance the economic allocation could be suitable for an environmental and economic cross analysis. In that case the allocation factor is similar, but RF and EE are multiplied by the respective costs without changing the non-linearity of the equation. For such reason, in order to preserve the problem linearity, no allocation will be done, which means that all the impacts will

be allocated on the RF. According to these considerations, the environmental cost function (4), minimizing the SHS life cycle impact (I) can be defined using the same nomenclature adopted for the economic cost function (2).

$$I = \frac{\sum_{k\in\{SHS\}}\left(IFix_k \cdot i_k + IVar_k \cdot cap_k\right)EAnn_k + \sum_{t\in\tau_{yr}}\left(ui_t \cdot EI_t - ue_t \cdot EFI_t\right)}{RF} \tag{4}$$

Where $EAnn_k$ is equal to $1/L_k$ and EI_t and EFI_t are the electricity mix environmental impact and the environmental revenues coming from the electricity injection to the grid. It's very important to stress that this approach is valid assuming that the components impacts ($IFix_k$ and $IVar_k$) are constant with the size of the system. This assumption is realistic if we limit our analysis to a residential SHS, whose power is typically in a range between 0 and 10 kW [45].

2.3. System description and constraints

As underlined in the introduction, the system is composed of the In, the CC, the BESS and the PV system. Figure 2 demonstrates that the PV system and the BESS are connected to a DC bus. The BESS requires a CC (a DC/DC converter) to interface with the PV system because they have a different voltage. The DC bus is connected through the In (a DC/AC converter) to an AC bus exchanging electricity with the load and the grid. Figure 2 also demonstrates that some energy flows are bidirectional: batteries can be charged and discharged depending on the SHS energy balance. Furthermore, the electricity can be exported to the grid or imported from it. Figure 2 also provides quantitative information about the energy flows in the system, which allow to determine the problem constraints.

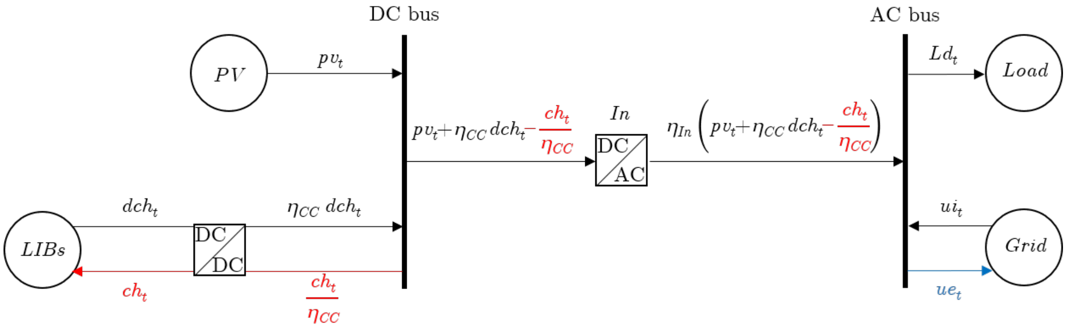

Figure 2: Graphical description of a grid-connected SHS.

As n different types of LIBs are evaluated, each one of them is considered as a different BESSs having the following constraints. The battery energy flows must respect the storage energy balance (5); this reservoir model is also constrained by the maximum storage capacity (6) and the maximum power allowed by the batteries (7), as well as inequalities precluding simultaneous charging and discharging (8)-(9). Indeed α is a binary variable assuming the value 0 during the discharge phase and 1 during the charge phase and M can be set to an indefinitely large value.

$for\ j = 1 : n$

$$soc_{t,j} = soc_{t-1,j} + ch_{t,j} \cdot \eta_{\mathrm{s,c}} - \frac{dch_{t,j}}{\eta_{\mathrm{s,d}}} \tag{5}$$

$$MiSoc \cdot cap_{s,j} \leqslant soc_{t,j} \leqslant cap_{s,j} \tag{6}$$

$$ch_{t,j}, dch_{t,j} \leqslant cap_{s,j} \cdot PCr \tag{7}$$

$$ch_{t,j} \leqslant \alpha \cdot M \tag{8}$$

$$dch_{t,j} \leqslant (1-\alpha) \cdot M \tag{9}$$

Where soc_t is the battery state of charge, $ch_{t,j}$ and $dch_{t,j}$ are the charge and discharge power of the battery j, $\eta_{s,c}$ and $\eta_{s,d}$ are the batteries charge and discharge efficiency and $MiSoc$ and PCr are the minimum allowed battery state of charge and the maximum batteries rated power.

The total charge (ch_t) and discharge (dch_t) power flows exchanged by the ESS is given by the sum of the power flows exchanged with the single BESSs (10), (11):

$$dch_t = \sum_{j=1}^{n} dch_{t,j} \tag{10}$$

$$ch_t = \sum_{j=1}^{n} ch_{t,j} \tag{11}$$

In this environmental optimization the impacts of the components are annualized dividing by their lifespan and for such reason these parameters are fundamental to determine the solution. Nevertheless, the batteries degradation depends on their operational conditions and can be calculated as function of the optimization variables, which makes the problem non-linear. In order to guarantee the linearity, and consequently the convergence of the problem, the batteries lifespan has to be fixed in a target value. This modeling technique is applied by Cardoso et al. [16] and adds an new constraint to their problem (12):

$$\sum_{t\in\tau_{yr}} dch_t \leqslant \frac{cap_s}{cap_s^r}\frac{\bar{T}}{\mathrm{L_s}} \cdot \frac{(\bar{Q}-\theta_s e^{\frac{E_a}{RK}}\sqrt{L_s})V}{\Big(\alpha_s K^2+\beta_s K+\gamma_s\Big)e^{\Big(\delta_s K+\epsilon_s\Big)PCr}} \tag{12}$$

Where cap_s^r is the reference battery capacity, $\bar{T}$ is the reference time of the analysis, $\bar{Q}$ is the maximum acceptable degradation level and V is the reference voltage of the battery. The parameters θ_s, ϵ_s, α_s, β_s, γ_s, ϵ_s and δ_s are the natural and ageing parameters of LIBs whereas E_a, K and R are the activation energy, the cell temperature and the gas constant.

Then the variable N^0 is set. It represents the maximum number of cycles per year depending on the target life and the maximum capacity fade (13):

$$N^0 = \frac{1}{cap_s^r}\frac{\bar{T}}{L_s}\cdot\frac{\left(\bar{Q}-\theta_s e^{\frac{E_a}{RK}}\sqrt{L_s}\right)V}{\left(\alpha_s K^2+\beta_s K+\gamma_s\right)e^{\left(\delta_s K+\epsilon_s\right)PCr}} \tag{13}$$

By the combination of Eqs. (12) and (13), the constraint (12) can be simplified to (14):

$$\sum_{t\in\tau_{yr}} dch_t \leqslant cap_s \cdot N^0 \tag{14}$$

The ageing parameters are defined by Cardoso et al. [16] for generic LIBs considering both the cyclic and calendar degradation of the devices. Nevertheless several materials can be used for the electrodes production and relevant differences can be noted concerning the cyclic battery ageing, whereas the natural degradation is approximately the same for every LIB [19, 20]. Rossi et al. [19, 20] provide information about the number of cycles which can be performed in standard operative conditions by the main types of LIBs on the market (temperature of 298 K, $MiSoc$= 20% and PCr=1 h^{-1}). Consequently, a correction factor k_j representative of the selected battery chemistry is defined as the ratio between the generic LIBs cycle life in standard conditions, evaluated using Eq. (13), and the reference values adopted by Rossi et al. [19, 20]. Therefore, the number of cycles performed by each battery type for generic operative conditions is calculated (15):

$for\ j = i : n$

$$N_j^0 = \frac{1}{cap_s^r}\frac{\bar{T}}{L_s}\cdot\frac{\left(\bar{Q}-\theta_s e^{\frac{E_a}{RK}}\sqrt{L_s}\right)V}{k_j\left(\alpha_s K^2+\beta_s K+\gamma_s\right)e^{\left(\delta_s K+\epsilon_s\right)PCr}}$$

Concluding, the constraint used to consider the battery ageing in our optimization problem (15) is obtained replacing N^0 with N_j^0 in Eq. (14):

$for\ j = i : n$

$$\sum_{t\in\tau_{yr}} dch_{t,j} \leqslant cap_{s,j} \cdot N_j^0 \tag{15}$$

After having set the constraints of the BESS, a constraint for the power of the CC is necessary: according to Eq. (16), the CC capacity must be always greater than or equal to the inlet power: as the CC can be crossed by a bi-directional flow, the input power is equal to dch_t during the discharge phase, and to ch_t/η_{cc} during the battery charge (Figure 2):

$$dch_t + \frac{ch_t}{\eta_{cc}} \leqslant cap_{cc} \tag{16}$$

Where η_{cc} is the efficiency of the CC.

Concerning the energy generation, the PV productivity profile (pv_t) is constrained by the environmental conditions as it is calculated as the product of the capacity and the productivity of a 1 kW system (SR_t), which is typical of the installation site (17).

$$pv_t \leqslant cap_{pv} \cdot SR_t \tag{17}$$

Moreover, the In capacity must be constrained to be greater than or equal to the input power (18) whereas the energy balance of the AC bus (19) constrains the SHS to provide to the user the power absorbed by the load:

$$pv_t + \eta_{cc} \cdot dch_t - \frac{ch_t}{\eta_{cc}} \leqslant cap_{in} \tag{18}$$

$$Ld_t = ui_t - ue_t + \eta_{\text{in}} \cdot \left(pv_t + \eta_{cc} \cdot dch_t - \frac{ch_t}{\eta_{\text{cc}}}\right) \tag{19}$$

Where η_{in} is the efficiency of the In.

Concluding, a last constraint (20) is necessary to set the capacity cap_k to 0 when, according to the value assumed by i_k, the component is not purchased.

$$cap_k \leqslant i_k \cdot M \tag{20}$$

2.4. Economic and Environmental Optima comparison

The result of the economic and environmental optimization models is the definition of the most sustainable and cost-effective configurations of the SHS. Particularly, the following outputs can be pointed out:

- the SHS configuration corresponding to the minimum environmental impact (Environmental Optimum);
- the life cycle impact and cost of the Environmental Optimum per MWh of energy provided to the load;
- the SHS configuration corresponding to the minimum economic cost (Economic Optimum);
- the life cycle impact and cost of the Economic Optimum per MWh of energy provided to the load.

In order to provide a general evaluation of the SHS, including both environmental and economic issues, the results calculated by the optimization models are represented in a Cartesian diagram having environmental impacts and costs as x and y axes: the Environmental Optimum will be addressed as P_1 and the Economic Optimum as P_2. Furthermore the SHSs are compared to the Grid whose representative point, addressed as P_g, is defined by the electricity mix average environmental impact and tariffs. This representation is very effective to assess how the SHS cost changes depending on its environmental impact.

Then, the effect of the variation of the costs of technologies and of the energy tariffs on the results will be assessed. Three LIBs future cost profiles have been proposed by NREL [46] supposing that, in long term

Table 1: Multiplication factors adopted for the sensitivity analysis.

Scenario	a_1	a_2	a_3	a_4	Description
A	1.25	1.25	1.00	1.00	Moderate increase of tariffs.
B	1.50	1.50	1.00	1.00	Strong increase of tariffs.
C	1.00	0.60	1.00	1.00	Moderate reduction of feed-in remunerations.
D	1.00	0.30	1.00	1.00	Strong reduction of feed-in remunerations.
E	1.00	0.00	1.00	1.00	Cancellation of feed-in remunerations.
F	1.00	1.00	0.80	0.65	Pessimistic decrease of technologies cost.
G	1.00	1.00	0.40	0.65	Realistic decrease of technologies cost.
H	1.00	1.00	0.20	0.65	Optimistic decrease of technologies cost.

scenarios, the LIBs costs could be about 80%, 40% and 20% of the current value. Furthermore, NREL also estimates that the costs of crystalline PV, which decreased fast in the last years, could become 65% of the current value in long term [47].

Two strategies have been adopted to simulate tariffs variations: first the electricity consumption costs and the revenues coming from the injection to the grid have been varied proportionally, then the revenues have been gradually lowered up to zero keeping the tariffs constant [48]. According to these assumptions, the following scenarios have been defined in Table 1 applying the multiplication factors a_1, a_2, a_3 and a_4 respectively to the tariffs, the revenues, the LIBs and the PV costs.

From the Economic and Environmental cost functions (2), (4) it is clear that only the economic optimal design is affected by the variations of costs and tariffs; as consequence, economic optimal design has been performed for all the previous scenarios and the distance from the minimum possible environmental impact, represented by the Environmental Optimum, is estimated.

3. Case study

After the general methodology is explained, a case study has been identified in order to test it in a realistic optimization design problem. As underlined in the Introduction, this paper grounds on the environmental assessment proposed by Rossi et al. [19, 20] where a grid-connected SHS equipped with NCA batteries has been evaluated as the most sustainable Nano-grid configuration in case the user is represented by a family of three people in Siena (Italy). Rossi et al. [19, 20] obtained their results using a methodology involving the system design, modelling and LCA. In the perspective of using optimization to improve the SHS eco-profile compared to other design methods, the innovative methodology described in the previous section has been applied to the same case study of Rossi et al. [19, 20]. Nevertheless, a more accurate load profile, obtained through a detailed statistical analysis and direct measurements of SHSs, has been used [49]. Quoilin et al. [49] provide for Italy several load profiles with hourly power absorption data: among them, one profile whose integral over the year is equal to the average yearly energy consumption [50] of a user composed of three people has been selected. In this optimization problem, the productivity profile of a 1 kW PV system is required as input (17) and is calculated using TRNSYS16 [51], whose library contains Meteonorm [52] meteorological data and models for PV performances estimation. Concerning the BESS, all the LIBs analyzed by Peters and Weil [32] and used by Rossi et al. [19, 20], are evaluated as candidates for this SHS application and the same nomenclature adopted by these authors has been maintained.

3.1. LCA Goal and Scope definition

The goal and scope of the cradle to grave optimized LCA analysis performed in this study is calculating the minimum environmental impact assumed by a SHS in the described conditions and the respective configuration. In order to do this, the environmental burden of the PV system, the In and the CC must be evaluated per kW of rated power whereas the BESS and the electricity mix impact must be assessed per kWh. These impact have been assessed using a classic cradle to grave LCA approach and represent inputs for the optimized LCA. In other words, this optimized LCA whose functional unit is 1 MWh of electricity provided to the load, is based on five separated LCA studies. Most of the impacts related to the construction (CO), the operation (OP) and end of life (EoL) of the SHS are considered as variable. In the range of residential PV systems, the impacts related to the installation, the transportation to the site and the maintenance are the only considered as independent from the size of the system. Nevertheless, because of their high uncertainty and minor relevance compared to the other impacts, they have been neglected in LCA similarly to Rossi et al. [19, 20].

3.2. Life Cycle Inventory

The LCI of this environmental assessment is based on that one published by Rossi et al. [19, 20] about the whole SHS; this inventory has been disassembled in order to get a different LCI for every element of the analyzed system. Furthermore, an updated version of the database (Ecoinvent 3.4 [28]) has been used to model the SHS environmental performances. Particularly, the CO of LIBs has been modelled thanks to the database file provided by Peters and Weil [32] and imported in openLCA [29]; their OP don't imply any environmental impact whereas the EoL processes have been carefully evaluated grounding on Huang et al. [53] and Weber et al. [54] studies. Concerning the PV system, the In and the CC, their CO was modelled directly using Ecoinvent 3.4 [28] processes; similarly to the BEES no burdens occur during the OP whereas the references for EoL are respectively Latunussa et al. [55] and Tschümperlin et al. [56]. The only impact occurring during the SHS operation deals with the electricity consumption from the grid. Ecoinvent 3.4 provides a detailed inventory to evaluate the impact of electricity mixes, including the Italian one that was used for this purpose. As Ecoinvent market processes are used, the embedded transports involved in the CO, OP and EoL phases is already included in the inventory.

3.3. Life Cycle Impact Assessment

Similarly to Rossi et al. [19, 20], the ReCiPe Endpoint [57] calculation method has been applied with a Europe H/A normalization and weighting set, aiming to evaluate results as single scores [58]. This choice is particularly useful to compare in a clearer way two Product Systems including all the impact categories proposed by the LCIA method, at the price of increasing the uncertainty of the LCA model. In this study, an updated version of ReCiPe (2016) [57] compared to that used by Rossi et al. [19, 20] has been used. Indeed, this choice is necessary to compare coherently the environmental impacts of SHSs designed using a classic and an optimized approach. Furthermore ReCiPe has been used because it includes the evaluation of seventeen impact categories, being the most complete among all the LCIA methods [57].

3.4. Life Cycle Costing

Concerning the economic optimization parameters, the costs of the SHS are set grounding on a NREL [15] benchmark LCC study of a PV system. In this NREL analysis, several types of costs are accounted to calculate the total. Particularly in this paper the cost of technologies have been considered as variable and include the manufacturing expenses afforded by the producers, the profits they wants to get by selling their products and the total amount of taxes that burden on the product (including a fee for the components disposal). Contrarily the costs related to the supply chain, the installation, the marketing and permitting processes costs are supposed to be fixed. NREL provides information about the costs of two different PV systems; the first one doesn't include the BESS whereas the second one does: the LIBs costs are estimated by the difference. Nevertheless NREL considers generic LIBs cells in its benchmark analysis; Xu et al. [38] instead published a very interesting study where LIBs costs are estimated depending on the battery chemistry. Since many types of LIBs are evaluated, the costs of the cells proposed by NREL have been replaced by the costs proposed by Xu et al. [38]. Concerning the CC, as its cost is not explicitly defined in the NREL analysis but it's included in the electrical balance of system, a market component pointed out by Rossi et al. [19, 20] as a representative converter has been selected for the cost estimation [59]. Concerning the tariffs, the Italian Energy Manager [60] provides historical data about the market value of energy. The remuneration coming from the electricity exportation to the grid is equal to the energy market value, whereas taxes must be added in case of electricity withdrawal [61]. All the costs and impacts are summarized in Table 2 whereas Table 3 collects all the LIBs ageing parameters, the components lifespan and efficiency values.

Table 2: Environmental impact and cost parameters.

Costs			**Impacts**		
Parameter	Value	Unit	Parameter	Value	Unit
$CFix_s$	5766.3	EUR	$IFix_s$	0	Pts
$CVar_{s,1}$	610.4	EUR/kWh	$IVar_{s,1}$	20.1	Pts/kWh
$CVar_{s,2)}$	610.4	EUR/kWh	$IVar_{s,2}$	24.1	Pts/kWh
$CVar_{s,3}$	898.4	EUR/kWh	$IVar_{s,3}$	32.1	Pts/kWh
$CVar_{s,4}$	529.4	EUR/kWh	$IVar_{s,4}$	23.2	Pts/kWh
$CVar_{s,5}$	583.4	EUR/kWh	$IVar_{s,5}$	18.2	Pts/kWh

$CVar_{s,6}$	592.4	EUR/kWh	$IVar_{s,6}$	15.5	Pts/kWh
$CVar_{s,7}$	592.4	EUR/kWh	$IVar_{s,7}$	14.0	Pts/kWh
$CFix_{pv}$	4128.6	EUR	$IFix_{pv}$	0.0	Pts
$CVar_{pv}$	1216.6	EUR/kW	$IVar_{pv}$	210.8	Pts/kW
$CFix_{in}$	1830.5	EUR	$IFix_{in}$	0.00	Pts
$CVar_{in}$	539.4	EUR/kW	$IVar_{in}$	24.6	Pts/kW
$CFix_{cc}$	479.5	EUR	$IFix_{cc}$	0.0	Pts
$CVar_{cc}$	141.3	EUR/kW	$IVar_{cc}$	9.6	Pts/kW
EC_t	[60]	EUR/kWh	EI_t	4.2e-02	Pts/kWh
FI_t	[60]	EUR/kWh	EFI_t	0.0	Pts/kWh

Table 3: Other operative parameters.

Parameter	Value	Unit	Reference
V	5	V	[16]
$\bar{Q}$	20	%	[16]
α	5.04e-06	$\mathrm{Ah^{-1}K^{-2}}$	[16]
β	-2.998e-03	$\mathrm{Ah^{-1}K^{-1}}$	[16]
γ	0.446	$\mathrm{Ah^{-1}}$	[16]
δ	-6.7e-03	$\mathrm{K^{-1}h}$	[16]
ϵ	2.35	h	[16]
θ	17127	$\mathrm{yr^{-1/2}}$	[16]
$k,1$	0.125	-	-
$k,2$	0.250	-	-
$k,3$	0.075	-	-
$k,4$	0.750	-	-
$k,5$	0.150	-	-
$k,6$	0.375	-	-
$k,7$	0.250	-	-
E_a	24500	$\mathrm{Jmol^{-1}}$	[16]
cap_s^r	712.9	Wh	[16]
PCr	0.3	$\mathrm{h^{-1}}$	[16]
K	298	K	[16]
$\bar{T}$	1	yr	[16]
L_{pv}	25	yrs	[19, 20]

L_s	10	yrs	[16]
L_{in}	10	yrs	[19, 20]
L_{cc}	10	yrs	[19, 20]
η_{cc}	0.95	-	[19, 20]
η_{in}	0.90	-	[19, 20]
$\eta_{s,c}$	0.90	-	[19, 20]
$\eta_{s,d}$	0.90	-	[19, 20]
MiSoc	0.20	-	[16]

4. Results and discussion

The previous sections provide a detailed description of LCA, LCC and MILP which are usually performed separately. The integration of these methodologies in a cross-evaluation of the economic and environmental optimal designs is proposed for the first time and therefore its detailed definition represents itself one of the results of the study. Furthermore, applying this methodology to a case study, some interesting findings and results have been evaluated.

4.1. Reference case

In this subsection, the economic and the environmental optimal designs are compared considering a reference case where the input parameters assume the values listed in Table 2 and Table 3. First of all the optimal configurations designed with the optimization program are illustrated in Table 4.

Table 4: Economic and Environmental Optima configurations.

	Environmental Optimum	Economic Optimum	
Flow	Quantity	Quantity	Unit
M-B (NCM)	8.66	0.00	kWh
PV	3.25	0.88	kW
In	1.44	0.54	kW
CC	1.61	0.00	kW

These results underline that, as assumed in the methodological section, both the Environmental and Economic Optima can be classified as residential installations because the PV power is in a range between 0 and 10 kW. In this phase of the discussion, these two configurations will be analyzed separately. Concerning the Environmental Optimum, a 3.25 kW PV system is installed; this value is about 50% lower than the size of the PV system designed with the method used by Rossi et al. [19, 20] (5.94 kW). Also the BESS installed capacity (8.66 kWh) is lower compared to the system designed by Rossi et al. [19, 20] for daily storage

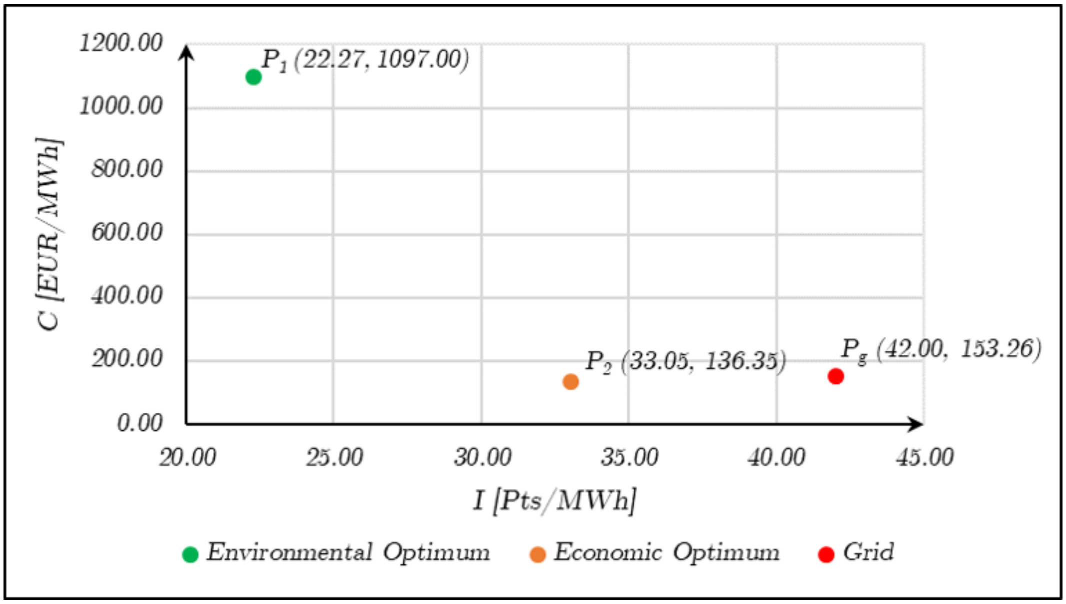

Figure 3: Graphical representation of Economic and Environmental Optima impacts and costs compared to the Italian electricity mix.

(12.58 kWh). According to the optimization results, M-B (NCM) batteries are identified by the model as the most sustainable LIBs for this SHS. This result partially confirms the conclusions of Rossi et al. [19, 20]: indeed, although they assessed Bauer (NCA) batteries as the most sustainable technology, they stress the point that mixing cobalt and other less rare materials represents the best trade off between the batteries LCA parameters. Concerning the Economic Optimum, a battery-free PV system, whose power is 0.88 kW, is the configuration which minimizes the SHS costs. From an economic point of view, exchanging energy with the grid is more convenient than having a high self-consumption rate, which is assessed to 79% for the Environmental Optimum and 28% for the Economic one.

A cross-evaluation of the environmental and economic performances of the system allowing for the identification of the best solution was made on the basis of the results reported in Figure 3. Indeed, the impacts and the costs of the SHSs and the Italian electricity mix, they are expressed as three points in the Cartesian diagram represented in Figure 3. The results collected in Table 4, although very interesting, just represent the capacity of the SHSs components.

In their study, Rossi et al. [19, 20] calculated an environmental impact of 22.81 Pts/MWh that is slightly higher than the minimum environmental impact calculated in this study; nevertheless Rossi et al. [19, 20] considered a physical allocation to evaluate the environmental benefits coming from the exportation of electricity to the grid. As underlined in the methodological section, the use of allocation in the optimization problem would lead to a non-linear cost function, but an allocation can be done afterwards to compare the results with those evaluated by Rossi et al. [19, 20]. Indeed, multiplying the results by the allocation factor $A = RF/(EE + RF)$, a minimum environmental impact of 16.52 Pts/MWh is calculated (about 30% lower than Rossi et al. [19, 20]). Figure 3 also allows to compare the Environmental and the Economic Optima with a benchmark case, where the user is supplied by the utility. According to the results, the burden of the Environmental Optimum is lower than the impact of the electricity mix (53%), whereas its cost is much higher (7.16 times the energy costs). Concerning the Economic Optimum, the environmental impact and the cost of the SHS are evaluated as about 78% and 88% of the average energy tariff. The costs of these optimal configurations can be compared with those of a reference SHS described in an annual report focused on levelized cost of energy sources [62]: even though specific data for Italy are not available in literature, this report proposes a range of values that a battery assisted PV installation can present. These costs vary from 412 to 736 EUR/MWh and are between those of the economic and the environmental optima. For all these reasons, it is possible to conclude that the Economic Optimum is in general more sustainable than the grid whereas the economic impact represents a very critical value for the Environmental Optimum. The interpretation of these results leads to the conclusion that mitigating the environmental impact of a SHS moving from the Economic to the Environmental Optimum by the use of ESSs is quite expensive from an economic point of view. For such reason, in the next section we'll try to mitigate the environmental impact of the Economic Optimum by the variation of cost parameters.

4.2. Sensitivity Analysis

The results evaluation brought to the conclusion that optimized LCA is effective to minimize the SHS impact as the Environmental Optimum is more sustainable than the Economic Optimum and than the grid, but its costs are much higher. Both the Economic Optimum costs and impacts instead are lower compared to the grid. Consequently we can conclude that the two optimal designs are very far from them but in the future the costs of technologies and the energy tariffs may change significantly and the results might be affected by this change. Applying economic optimal design to the scenarios proposed in Table 1, the resulting SHS configurations are illustrated in Table 5.

Table 5: Economic Optimum configurations in the considered scenarios: A) Moderate increase of tariffs; B) Strong increase of tariffs; C) Moderate reduction of feed-in remunerations; D) Strong reduction of feed-in remunerations; E) Cancellation of feed-in remunerations; F) Pessimistic decrease of technologies cost; G) Realistic decrease of technologies cost; H) Optimistic decrease of technologies cost.

Flow	A	B	C	D	E	F	G	H	Unit
Bauer (LTO)	0.00	0.00	0.00	0.00	0.00	0.00	0.21	5.04	kWh
PV	1.16	1.46	0.84	0.81	0.79	1.33	1.36	2.27	kW
In	0.71	0.90	0.51	0.49	0.48	0.70	0.70	0.78	kW
CC	0.00	0.00	0.49	0.00	0.00	0.00	0.07	0.82	kW

Analysing the SHS economic optimal designs it's possible to point out that a breakdown of the costs of technologies is the only case where BEES becomes economically profitable; indeed, in Scenario H an ESS with relevant capacity is included in the economic optimal design. Another observation is that, because of the lower cost of the materials, the battery type minimizing the SHS cost in this scenario is Bauer (LTO), differently from the environmental optimal design where M-B (NCM) is assessed as the most sustainable LIB. Thus the SHSs cross-analysis allows to conclude that, in this scenario, the choice of the BESS depends on the rationality adopted designing the SHS.

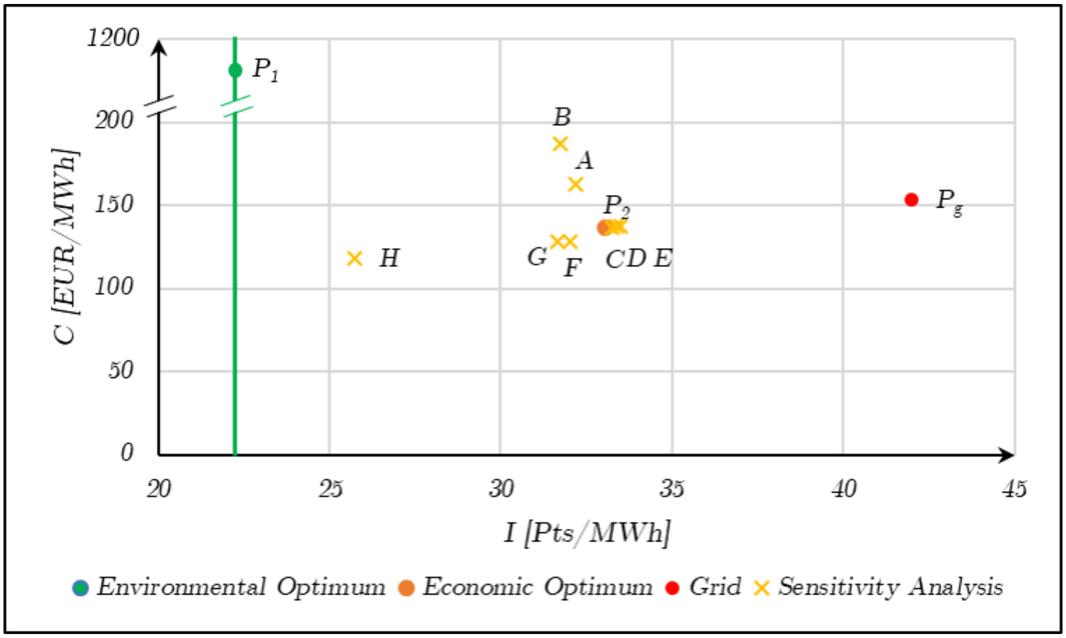

Figure 4: Graphical representation of the sensitivity analysis results compared to the reference case. The analysed scenarios are: A) Moderate increase of tariffs; B) Strong increase of tariffs; C) Moderate reduction of feed-in remunerations; D) Strong reduction of feed-in remunerations; E) Cancellation of feed-in remunerations; F) Pessimistic decrease of technologies cost; G) Realistic decrease of technologies cost; H) Optimistic decrease of technologies cost.

Figure 4 graphically demonstrates that the environmental impact calculated for the SHS economic optimal configuration in Scenario H is the closest to the minimum, which results from the environmental optimal design and is represented by a green line in Figure 4. Indeed, its environmental impact is 25.72 Pts/MWh, about 20% less than the Reference case, whereas the Environmental Optimum and the grid have an impact of 22.27 PTs/MWh and 42.00 Pts/MWh respectively. Concerning the economic considerations, the Economic Optimum in scenario H has a cost of 117.95 EUR/MWh, lower than the Reference case (136.35 EUR/MWh) and the grid electricity (153.26 EUR/MWh). This is due to the positive effect of producing and storing energy with very low cost PV modules and LIBs. Contrarily, other less optimistic scenarios do not allow a significant environmental impact mitigation. Increasing the energy tariffs and revenues is slightly effective to lower the SHS environmental impact, whereas decreasing the revenues from the injection to the grid is assessed to increase the environmental impact.

5. Conclusions

In this paper, a new methodological framework for the optimal design of a SHS is proposed, where a MILP approach is used to minimize the life cycle environmental impacts and the economic costs of a SHS. Moreover an innovative approach for the comparison of the optimal configurations is also included. The environmental and economic optimal designs were applied to a case study comprising a SHS serving a 3 users building in Siena (Italy). According to the cross-evaluation analysis, lowering the environmental impact moving from the grid to the economic optimum is possible using a simple PV system that would bring an economic benefit as well. A further impact mitigation is possible moving from the economic optimum to the environmental optimum thanks to the installation of a more powerful PV system and a BESS, but the cost of this environmental improvement is very high. Therefore other strategies have been adopted to mitigate the economic optimum environmental impact: reducing the costs of technologies and varying the energy tariffs. Changing the tariffs and the revenues allows, in some cases, to enhance the PV power; nevertheless, without a relevant decrease of technologies costs, this operation is not very effective for the environment. Indeed, a cost reduction of batteries and of PV allows the economic optimum environmental impact to get much closer to the minimum also having an economic advantage. One possible extension of the study would be using this methodology to investigate the role of SHSs and ESSs in energy communities, analysing the interaction between several producers, consumers and ESSs.

6. Supporting Information

The Nomenclature used in this paper is collected in a Supporting Information file to facilitate the readers in the comprehension of the text.

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References

[1] Nishant Narayan et al. "Estimating battery lifetimes in Solar Home System design using a practical modelling methodology". In: *Applied Energy* 228 (2018), pp. 1629–1639. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2018.06.152`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261918310225`.

[2] Benjamin K. Sovacool. "Success and failure in the political economy of solar electrification: Lessons from World Bank Solar Home System (SHS) projects in Sri Lanka and Indonesia". In: *Energy Policy* 123 (2018), pp. 482–493. ISSN: 0301-4215. DOI: `https://doi.org/10.1016/j.enpol.2018.09.024`. URL: `http://www.sciencedirect.com/science/article/pii/S0301421518306293`.

[3] Imran Khan. “Impacts of energy decentralization viewed through the lens of the energy cultures framework: Solar home systems in the developing economies”. In: *Renewable and Sustainable Energy Reviews* 119 (2020), p. 109576. ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2019.109576`. URL: `http://www.sciencedirect.com/science/article/pii/S1364032119307841`.

[4] Tahsina Khan et al. “Determinants of microfinance facility for installing solar home system (SHS) in rural Bangladesh”. In: *Energy Policy* 132 (2019), pp. 299–308. ISSN: 0301-4215. DOI: `https://doi.org/10.1016/j.enpol.2019.05.047`. URL: `http://www.sciencedirect.com/science/article/pii/S0301421519303519`.

[5] Ryan Kennedy et al. “Multilevel customer segmentation for off-grid solar in developing countries: Evidence from solar home systems in Rwanda and Kenya”. In: *Energy* 186 (2019), p. 115728. ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2019.07.058`. URL: `http://www.sciencedirect.com/science/article/pii/S0360544219313854`.

[6] Eric O’Shaughnessy et al. “Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings”. In: *Applied Energy* 213 (2018), pp. 11–21. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2017.12.118`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261917318421`.

[7] Ammu Susanna Jacob, Rangan Banerjee, and Prakash C. Ghosh. “Sizing of hybrid energy storage system for a PV based microgrid through design space approach”. In: *Applied Energy* 212 (2018), pp. 640–653. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2017.12.040`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261917317543`.

[8] Prashant Nagapurkar and Joseph D. Smith. “Techno-economic optimization and environmental Life Cycle Assessment (LCA) of microgrids located in the US using genetic algorithm”. In: *Energy Conversion and Management* 181 (2019), pp. 272–291. ISSN: 0196-8904. DOI: `https://doi.org/10.1016/j.enconman.2018.11.072`. URL: `http://www.sciencedirect.com/science/article/pii/S0196890418313244`.

[9] Eric O’Shaughnessy et al. “Solar plus: A review of the end-user economics of solar PV integration with storage and load control in residential buildings”. In: *Applied Energy* 228 (2018), pp. 2165–2175. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2018.07.048`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261918310766`.

[10] Mario Petrollese, Giorgio Cau, and Daniele Cocco. “Use of weather forecast for increasing the self-consumption rate of home solar systems: An Italian case study”. In: *Applied Energy* 212 (2018), pp. 746–758. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2017.12.075`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261917317907`.

[11] Ghassan Zubi et al. “The unlocked potential of solar home systems; an effective way to overcome domestic energy poverty in developing regions”. In: *Renewable Energy* 132 (2019), pp. 1425–1435. ISSN: 0960-1481. DOI: `https://doi.org/10.1016/j.renene.2018.08.093`. URL: `http://www.sciencedirect.com/science/article/pii/S0960148118310437`.

[12] Boucar Diouf and Christophe Avis. “The potential of Li-ion batteries in ECOWAS solar home systems”. In: *Journal of Energy Storage* 22 (2019), pp. 295–301. ISSN: 2352-152X. DOI: `https://doi.org/10.1016/j.est.2019.02.021`. URL: `http://www.sciencedirect.com/science/article/pii/S2352152X18307369`.

[13] Chukwuma Leonard Azimoh et al. “An assessment of unforeseen losses resulting from inappropriate use of solar home systems in South Africa”. In: *Applied Energy* 136 (2014), pp. 336–346. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2014.09.044`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261914009921`.

[14] Kasereka Ndwali, Jackson G. Njiri, and Evan M. Wanjiru. “Multi-objective optimal sizing of grid connected photovoltaic batteryless system minimizing the total life cycle cost and the grid energy”. In: *Renewable Energy* (2019). ISSN: 0960-1481. DOI: `https://doi.org/10.1016/j.renene.2019.10.065`. URL: `http://www.sciencedirect.com/science/article/pii/S0960148119315563`.

[15] NREL. “Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage”. In: (2016). URL: `https://www.nrel.gov/docs/fy17osti/67474.pdf` (visited on 03/20/2019).

[16] Gonçalo Cardoso et al. “Battery aging in multi-energy microgrid design using mixed integer linear programming”. In: *Applied Energy* 231 (2018), pp. 1059–1069. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2018.09.185`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261918315058`.

[17] Georgios Martinopoulos. “Are rooftop photovoltaic systems a sustainable solution for Europe? A life cycle impact assessment and cost analysis”. In: *Applied Energy* 257 (2020), p. 114035. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2019.114035`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261919317222`.

[18] Di Zhang et al. “Optimal design of CHP-based microgrids: Multiobjective optimisation and life cycle assessment”. In: *Energy* 85 (2015), pp. 181–193. ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2015.03.036`. URL: `http://www.sciencedirect.com/science/article/pii/S0360544215003308`.

[19] Federico Rossi et al. “Environmental analysis of a nano-grid: A Life Cycle Assessment”. In: *Science of The Total Environment* 700 (2020), p. 134814. ISSN: 0048-9697. DOI: `https://doi.org/10.1016/j.scitotenv.2019.134814`. URL: `http://www.sciencedirect.com/science/article/pii/S0048969719348053`.

[20] Federico Rossi et al. “Life Cycle Inventory datasets for nano-grid configurations”. In: *Data in Brief* 28 (2020), p. 104895. ISSN: 2352-3409. DOI: `https://doi.org/10.1016/j.dib.2019.104895`. URL: `http://www.sciencedirect.com/science/article/pii/S2352340919312508`.

[21] P. Goglio et al. “Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes”. In: *Journal of Cleaner Production* 244 (2020), p. 118896. ISSN: 0959-6526. DOI: `https://doi.org/10.1016/j.jclepro.2019.118896`. URL: `http://www.sciencedirect.com/science/article/pii/S0959652619337667`.

[22] F. Rossi et al. “Environmental impact analysis applied to solar pasteurization systems”. In: *Journal of Cleaner Production* 212 (2019). ISSN: 09596526. DOI: `10.1016/j.jclepro.2018.12.020`.

[23] Jaesung Jung and Michael Villaran. “Optimal planning and design of hybrid renewable energy systems for microgrids”. In: *Renewable and Sustainable Energy Reviews* 75 (2017), pp. 180–191. ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2016.10.061`. URL: `http://www.sciencedirect.com/science/article/pii/S1364032116307316`.

[24] Simone Maranghi et al. “Environmental Profile of the Manufacturing Process of Perovskite Photovoltaics: Harmonization of Life Cycle Assessment Studies”. In: *Energies* 12.19 (2019). ISSN: 1996-1073. DOI: `10.3390/en12193746`. URL: `https://www.mdpi.com/1996-1073/12/19/3746`.

[25] International Organization for Standardization. “ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework”. In: (2016). URL: `https://www.iso.org/standard/37456.html` (visited on 12/05/2019).

[26] International Organization for Standardization. “Environmental management — Life cycle assessment — Requirements and guidelines”. In: (2016). URL: `https://www.iso.org/standard/38498.html` (visited on 12/05/2019).

[27] Sara Toniolo et al. “Chapter 3 - Life cycle thinking tools: Life cycle assessment, life cycle costing and social life cycle assessment”. In: (2020). Ed. by Jingzheng Ren and Sara Toniolo, pp. 39–56. DOI: `https://doi.org/10.1016/B978-0-12-818355-7.00003-8`. URL: `http://www.sciencedirect.com/science/article/pii/B9780128183557000038`.

[28] Ecoinvent. “Ecoinvent 3.4 Report of Changes”. In: (2016). URL: `https://www.ecoinvent.org/database/older-versions/ecoinvent-34/report-of-changes-ecoinvent-34/report-of-changes-ecoinvent-34.html` (visited on 12/05/2019).

[29] GreenDelta GmbH. “openLCA Comprehensive User Manual”. In: (2019). URL: `http://www.openlca.org/wp-content/uploads/2019/07/openLCA-1-9_User-Manual.pdf` (visited on 12/05/2019).

[30] Manuel Monge and Luis A. Gil-Alana. “Automobile components: Lithium and cobalt. Evidence of persistence”. In: *Energy* 169 (2019), pp. 489–495. ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2018.12.068`. URL: `http://www.sciencedirect.com/science/article/pii/S0360544218324344`.

[31] Jens F. Peters et al. “The environmental impact of Li-Ion batteries and the role of key parameters – A review”. In: *Renewable and Sustainable Energy Reviews* 67 (2017), pp. 491–506. ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2016.08.039`. URL: `http://www.sciencedirect.com/science/article/pii/S1364032116304713`.

[32] Jens F. Peters and Marcel Weil. “Providing a common base for life cycle assessments of Li-Ion batteries”. In: *Journal of Cleaner Production* 171 (2018), pp. 704–713. ISSN: 0959-6526. DOI: `https://doi.org/10.1016/j.jclepro.2017.10.016`. URL: `http://www.sciencedirect.com/science/article/pii/S0959652617323077`.

[33] Guillaume Majeau-Bettez, Troy R. Hawkins, and Anders Hammer Strømman. “Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles”. In: *Environmental Science & Technology* 45.10 (2011), pp. 4548–4554. DOI: `https://doi.org/10.1021/es103607c`.

[34] Linda Ager-Wick Ellingsen et al. “Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack”. In: *Journal of Industrial Ecology* 18.1 (2014), pp. 113–124. DOI: `10.1111/jiec.12072`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12072`. URL: `https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12072`.

[35] Mats Zackrisson et al. “Life cycle assessment of lithium-air battery cells”. In: *Journal of Cleaner Production* 135 (2016), pp. 299–311. ISSN: 0959-6526. DOI: `https://doi.org/10.1016/j.jclepro.2016.06.104`.

[36] Christian Bauer. *ökobilanz von lithium-ionen batterien*. 2010. URL: `http://www.thelma-emobility.net/pdf/Vergleich_LCA_ElektroPW_EKZ_PSI_Empa.pdf` (visited on 03/20/2019).

[37] Dominic A. Notter et al. “Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles”. In: *Environmental Science & Technology* 44.19 (2010), pp. 7744–7744. DOI: `10.1021/es1029156`. eprint: `https://doi.org/10.1021/es1029156`. URL: `https://doi.org/10.1021/es1029156`.

[38] Gaojie Xu et al. “Li4Ti5O12-based energy conversion and storage systems: Status and prospects”. In: *Coordination Chemistry Reviews* 343 (2017), pp. 139–184. ISSN: 0010-8545. DOI: `https://doi.org/10.1016/j.ccr.2017.05.006`. URL: `http://www.sciencedirect.com/science/article/pii/S0010854517301121`.

[39] Kristen A Severson et al. "Data-driven prediction of battery cycle life before capacity degradation". In: *Nature Energy* 4.May (2019), pp. 383–391. ISSN: 2058-7546. DOI: `10.1038/s41560-019-0356-8`. URL: `http://dx.doi.org/10.1038/s41560-019-0356-8`.

[40] Guannan He et al. "electrochemical energy storage management". In: *Nature Energy* 3.May (2018). ISSN: 2058-7546. DOI: `10.1038/s41560-018-0129-9`. URL: `http://dx.doi.org/10.1038/s41560-018-0129-9`.

[41] Lawrence Berkeley National Laboratory (LBNL). "Distributed Energy Resources - Customer Adoption Model (DER-CAM)". In: (2019). URL: `https://building-microgrid.lbl.gov/projects/der-cam` (visited on 03/20/2019).

[42] International Organization for Standardization. "Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing". In: (2017). URL: `https://www.iso.org/standard/38498.html`.

[43] N. Dainelli et al. "Exergo-economic evaluation of the cost for solar thermal depuration of water". In: *Energies* 10.9 (2017). ISSN: 19961073. DOI: `10.3390/en10091395`.

[44] Christel Cederberg and Magnus Stadig. "System expansion and allocation in life cycle assessment of milk and beef production". In: *The International Journal of Life Cycle Assessment* 6 (2003), pp. 350–356. ISSN: 1614-7502. DOI: `https://doi.org/10.1007/BF02978508`. URL: `https://link.springer.com/article/10.1007/BF02978508#citeas`.

[45] Solar Power Europe. "Global Market Outlook For Solar Power / 2018 - 2022". In: (2018). URL: `https://www.solarpowereurope.org/wp-content/uploads/2018/09/Global-Market-Outlook-2018-2022.pdf` (visited on 01/03/2020).

[46] National Renewable Energy Laboratory (NREL). *Annual technology baseline: electricity.* 2019. URL: `https://atb.nrel.gov/electricity/2019/index.html?t=st` (visited on 03/20/2019).

[47] National Renewable Energy Laboratory (NREL). *Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Road Map*. 2018. URL: `https://www.nrel.gov/docs/fy19osti/72134.pdf` (visited on 03/20/2019).

[48] Stephen Comello and Stefan Reichelstein. "Cost competitiveness of residential solar PV: The impact of net metering restrictions". In: *Renewable and Sustainable Energy Reviews* 75 (2017), pp. 46–57. ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2016.10.050`. URL: `http://www.sciencedirect.com/science/article/pii/S136403211630702X`.

[49] Sylvain Quoilin et al. "Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment". In: *Applied Energy* 182 (2016), pp. 58–67. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2016.08.077`. URL: `http://www.sciencedirect.com/science/article/pii/S0306261916311643`.

[50] European Commission. "Eurstat". In: (2018). URL: `https://ec.europa.eu/eurostat` (visited on 03/20/2019).

[51] University of Wisconsin-Madison. "TRaNsient SYstems Simulation Program". In: (2007). URL: `http://sel.me.wisc.edu/trnsys/user-resources/index.html` (visited on 03/20/2019).

[52] Meteonorm. *Meteonorm information.* 2006. URL: `https://meteonorm.com/` (visited on 03/20/2019).

[53] Bin Huang et al. "Recycling of lithium-ion batteries: Recent advances and perspectives". In: *Journal of Power Sources* 399 (2018), pp. 274–286. ISSN: 0378-7753. DOI: `https://doi.org/10.1016/j.jpowsour.2018.07.116`. URL: `http://www.sciencedirect.com/science/article/pii/S0378775318308498`.

[54] Selina Weber et al. "Life Cycle Assessment of a Vanadium Redox Flow Battery". In: *Environmental Science and Technology* 52.18 (2018), pp. 10864–10873. ISSN: 15205851. DOI: `10.1021/acs.est.8b02073`.

[55] Cynthia E.L. Latunussa et al. "Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels". In: *Solar Energy Materials and Solar Cells* 156 (2016), pp. 101–111. ISSN: 09270248. DOI: `10.1016/j.solmat.2016.03.020`. URL: `http://dx.doi.org/10.1016/j.solmat.2016.03.020`.

[56] Laura Tschümperlin, Philippe Stolz, and Rolf Frischknecht. "Life cycle assessment of low power solar inverters (2.5 to 20 kW) Swiss Federal Office of Energy SFOE". In: 3.October (2016).

[57] Pre-sustainability. "ReCiPe 2017 - A harmonized life cycle impact assessment method at midpoint and endpoint level". In: (2017). URL: `https://www.pre-sustainability.com/download/Report_ReCiPe_2017.pdf` (visited on 01/03/2020).

[58] Heidi K. Stranddorf, Leif Hoffmann, and Andres Schmidt. "Impact categories, normalisation and weighting in LCA." In: (2005). URL: `https://www2.mst.dk/udgiv/publications/2005/87-7614-574-3/pdf/87-7614-575-1.pdf` (visited on 01/03/2020).

[59] Mastervolt. "Mastervolt Charge Regulator SCM 60 MPPT MB". In: (2019). URL: `https://www.mastervolt.it/prodotti/regolatori-di-carica-solari/scm60-mppt-mb/` (visited on 03/20/2019).

[60] Gestore Mercati Energetici. "Statistiche". In: (2019). URL: `https://www.mercatoelettrico.org/It/download/DownloadStatYY.aspx` (visited on 03/20/2019).

[61] Gestore dei servizi energetici spa. "GSE – Ritiro Dedicato, Manuale Utente". In: (2007). URL: `https://www.gse.it/servizi-per-te/fotovoltaico/ritiro-dedicato` (visited on 03/20/2019).

[62] LAZARD Inc. "Levelized Cost of Energy and Levelized Cost of Storage 2019". In: (2019). URL: `https://www.lazard.com/perspective/lcoe2019` (visited on 05/20/2020).