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Environmental and Economic Optima of Solar Home Systems Design: a combined LCA and LCC approach

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

28 The literature on SHS systems planning and impact is extensive and involves different economic and
29 environmental perspectives. On the economic side, O'Shaughnessy [6] published an interesting review sum-
30 marizing the results of seventeen SHS economic analyses available in literature, and later proposed their
31 own economic optimal design to size a SHS [9]. Petrollese et al. [10] proposed an Italian case study where
32 optimization is used to maximize the SHS economic benefits associated with self-consumption. Zubi et
33 al. [11] estimated the cost of the energy produced by a SHS, focusing on the contribution of the BESS,
34 whereas Diouf et al. [12] had a broader perspective on the economic benefits related to the adoption of
35 SHSs in some African states. SHSs economic issues have also been addressed by Azimoh et al. [13] with
36 a particular emphasis on role of the installation and use of those systems in mitigating life cycle costs.
37 Ndwali et al. [14] optimized the design of a batteries assisted PV system considering the overall costs of
38 energy and technologies; NREL performed a very detailed analysis on these costs and released a benchmark
39 study [15]. According to this evaluation, batteries have a very important impact on the SHS cost; indeed,
40 NREL estimates the cost of a 5.6 kW PV installation to about 14,000 EUR whereas adding a 6kWh BESS,
41 typical of residential systems, it is about 25,000 EUR [15]. Still in the context of SHS economic analysis,
42 the paper of Cardoso et al. [16] is particularly relevant as the optimal economic configuration of a SHS is
43 defined using mixed integer linear programming (MILP). MILP represents the most widely used approach
44 for power systems optimization because, contrarily to mixed integer non-linear programming (MINLP), its
45 convergence and optimality are guaranteed [16]. Differently from simulation-based optimization, MILP is
46 a mathematical minimization of a cost function that does not involve intermediate results. Other studies,
47 although less abundant, propose the SHS environmental impact estimation. For instance Martinopoulos et al.
48 [17] presents a broad overview of economic and environmental impact analyses of electricity production from
49 PV in European context. Nagapurkar and Smith [8] used LCA to evaluate the carbon dioxide emissions of
50 a cost-optimized Microgrid whereas Di Zhang et al. [18] analyzed the environmental impacts of a combined
51 heat and power (CHP) based off-grid system. Recent papers published by Rossi et al. [19, 20] show how
52 the design, modeling and environmental impact assessment of some user scale electric systems based on PV
53 generation, including SHSs, can be connected with each other in a three-steps methodology. The authors
54 concluded that a grid-connected SHS represents the best configuration for the environment.

55 On the side of the environmental impacts, life cycle assessment (LCA) is particularly useful because it
56 allows to consider all the direct and indirect burdens connected with all the phases of the life cycle of a

57 technology. Indeed it is possible to evaluate the negative and positive effects on the environment of the
58 natural resources consumption and of the direct and indirect emissions occurring during the raw materials
59 extraction, transports, manufacturing, operation and the disposal [21]. Moreover, several environmental im-
60 pact categories can be investigated including global warming potential, resources depletion, acidification and
61 eutrophication potential and other types of impacts [22]. This represents a remarkable difference with other
62 environmental assessment methods which include only direct carbon dioxide emissions to the environment
63 [23]. This is particularly relevant in the evaluation of technologies, such as PV and BESS, that are not
64 responsible for pollutant emissions in their operation, but have a significant impact during other phases of
65 their life [24]. For all these reasons, the International Organization for Standardization (ISO) decided to
66 define a standard procedure to perform a LCA analysis in ISO 14040 and ISO 14044 regulations [25, 26]. The
67 life cycle approach became so important that it has been extended from the environmental analyses to the
68 economic and social evaluations with Life Cycle Costing (LCC) and social LCA [27]. The tools necessary to
69 perform a LCA analysis are a database, provided by Ecoinvent [28] to collect the information for the model
70 definition, and a computational software, in this case openLCA [29].

71 In the field of LCA, a particular attention is devoted to the energy storage system (ESS) due to the
72 variety of battery chemistries, materials and technical properties. For instance cobalt is a metal providing
73 high energy density to the battery, but at the same time it is becoming rare and expensive [30]. In order to
74 perform LCA of batteries, the input data have been recovered from Peters et al. [31, 32]. In these papers the
75 main LCA studies based on primary data of the main Lithium-ion batteries (LIBs) commercially available
76 have been gathered and modified to provide a single harmonized database. The same nomenclature adopted
77 by Peters and Weil [32] has been used to address these LIBs: particularly nickel cobalt manganese (NCM),
78 lithium iron phosphates (LFP) [33, 34, 35], nickel cobalt aluminium (NCA), lithium iron titanate (LTO)
79 [36] and lithium manganese oxide (LMO) [37] batteries have been compared. Concerning the costs of these
80 devices, some very detailed and reliable analyses are available in literature [15, 38] and are considered as
81 a reference in this study. Additionally, it was demonstrated that the ageing of ESSs strongly affects the
82 results of optimization during the design and management phases [16] and represents a major concern for
83 economic and environmental problems. For such reason, batteries degradation models [39] are often applied
84 in investments decisions tools [40, 16]. Some of these models are also very specific for SHS applications [1,
85 19] but usually they aren't involved in SHS design optimization [16]. MILP is a very powerful instrument
86 because it allows, using appropriate assumptions, to include both cyclic and calendar ageing expressions in
87 SHSs optimal design [16].

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

- 91 • An optimization model for optimal environmental design, based on LCA. This model mimics the
92 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.

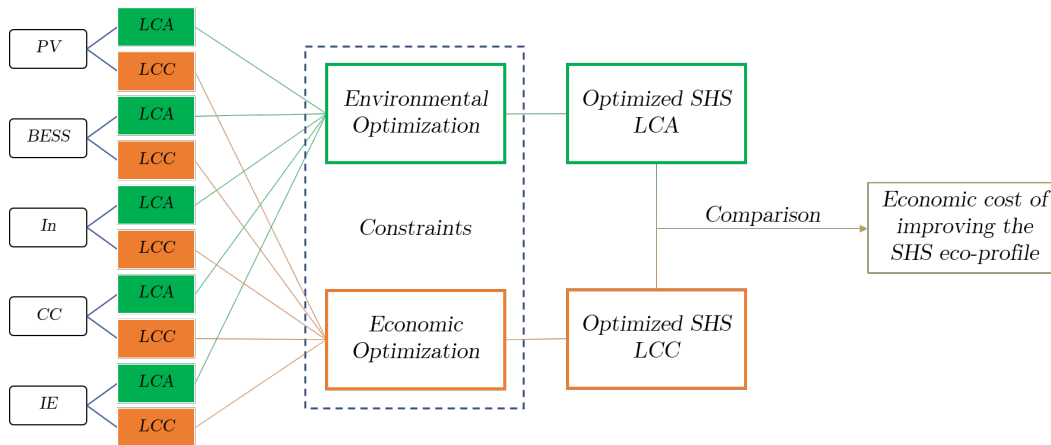


Figure 1: Sketch of the applied methodology.

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

114 rationality in the acquisition and utilization of DER technologies. In this section, this rationality is presented
115 as an economic optimal design, where individual consumers size their SHS and dispatch energy to minimize
116 the costs. The economic optimal design model proposed by Cardoso et al. [16] and included in the overall
117 modeling framework of the Distributed Energy Resources Customer Adoption Model (DER-CAM) tool [41],
118 has been adopted as a reference for this study. This model considers all the annualized expenses that a user
119 should afford in case its energy consumption is guaranteed by a grid-connected SHS. According to ISO 15686
120 [42] standard for LCC, these expenses are distributed over the SHS lifespan: the cost of technologies includes
121 several contributions like the construction, the supply chain, the marketing and the disposal. Furthermore,
122 during the operation of the SHS, the user might import and export energy from the grid, which implies
123 costs and revenues for the user. In other terms, an optimized LCC is performed grounding on Cardoso et
124 al. [16] model. As common practice in LCA and LCC, the results are referred to a Reference Flow (RF).
125 As the function of the SHS is providing electricity to the user, the RF is defined as the amount of electricity
126 provided to the load (Eq. 1).

$$127 \quad RF = \sum_{t \in \tau_{yr}} \left(\frac{Ld_t}{1000} \right) \quad (1)$$

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

$$137 \quad C = \frac{\sum_{k \in \{SHS\}} (CFix_k \cdot i_k + CVar_k \cdot cap_k) Ann_k + \sum_{t \in \tau_{yr}} (ui_t \cdot EC_t - ue_t \cdot FI_t)}{RF} \quad (2)$$

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

$$140 \quad Ann_k = \frac{ir}{1 - (1 + ir)^{L_k}} \quad (3)$$

141 2.2. Environmental Optimal Design

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

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

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

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

167 The function of the SHS is to provide electricity to the load and thus the RF, defined as the main output,
168 is the amount of energy supplied to the user (1). The FU, set to 1 MWh, must be coherent with the RF
169 but it doesn't depend on its amount; indeed it is a quantity used to make the SHS comparable with other
170 product systems having the same function: for instance expressing the SHS environmental impacts per MWh
171 of energy provided to the user allows the comparison with 1 MWh of energy from the electricity mix. The
172 LCA analysis is performed using the software openLCA [29] and the database Ecoinvent 3.4 [28] that allows
173 to define the inputs and the outputs of a SHS, named Flows, represented in this case by the SHS components
174 and energy flows. The production, the installation, the disposal and all the other operations involved in the
175 Flows life cycle are named Processes and are also contained in the database. As any LCA software, openLCA
176 evaluates the LCI of the SHS summarizing all the Elementary Flows (the liquid, gaseous or solid emissions to
177 the environment and the raw materials) involved in the SHS life cycle. LCIA calculation methods multiply
178 the Elementary Flows by impact factors and then sum the results to get an environmental impact value. As
179 1 MWh of energy to the load is set as FU of the study, the results must be divided by the RF.

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

191 First, the unitary environmental impacts must be classified as variable impacts ($IVar_k$), which depend
 192 on the Quantity, and fixed impacts ($IFix_k$), which don't depend on the Quantity.

193 Moreover, in order to be coherent with Eq. (2), the life cycle impacts of the SHS Flows must be annualized.
 194 Whereas the economic costs of technologies are annualized by Eq. (3) considering an interest rate, to obtain
 195 annualized environmental costs of technologies it is enough to divide the impacts by the components lifespan
 196 (L_k). In this way, the longer is the components lifespan, the lower is their annualized impact.

197 As the SHS is supposed to be connected to the grid, the system can inject exported energy (EE) and use
 198 imported energy (IE) from it. The economic optimization problem includes the evaluation of some revenues
 199 coming from the electricity exportation to the grid. In LCA, the evaluation of the by-products is not always
 200 necessary, but two different methods exist: system expansion and allocation [44] which are of difficult use in
 201 our case. Indeed using the system expansion is equivalent to set some environmental revenues because the
 202 exported electricity can be defined as an output flow that allows to avoid the production of the same amount
 203 of electricity from the mix, whose impact is consequently subtracted to the total. Nevertheless in this case
 204 the system expansion would lead to unrealistic results because the size of the PV system would be out of the
 205 range of residential applications and the SHS would lead to a very big negative environmental impact. For
 206 such reason allocation has been preferred by Rossi et al. [19, 20] to describe this multi-output process: using
 207 this approach, part of the impacts are allocated on the RF, and part of them on the by-product. Physical
 208 allocation is one of the most widely used allocation methods and consists on multiplying the impacts for an
 209 allocation factor, calculated as $RF/(RF + EE)$. The allocation factor has in the denominator the exported
 210 electricity which is an optimization variable: consequently the cost function would become non-linear. Non-
 211 linear problems are more complex to be solved than linear and their convergence is not guaranteed. The same
 212 issue exists if other types of allocation are chosen; for instance the economic allocation could be suitable for
 213 an environmental and economic cross analysis. In that case the allocation factor is similar, but RF and EE
 214 are multiplied by the respective costs without changing the non-linearity of the equation. For such reason,
 215 in order to preserve the problem linearity, no allocation will be done, which means that all the impacts will

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

$$219 \quad I = \frac{\sum_{k \in \{SHS\}} (IFix_k \cdot i_k + IVar_k \cdot cap_k) EAnn_k + \sum_{t \in \tau_{yr}} (w_t \cdot EI_t - ue_t \cdot EFI_t)}{RF} \quad (4)$$

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

225 2.3. System description and constraints

226 As underlined in the introduction, the system is composed of the In, the CC, the BESS and the PV
 227 system. Figure 2 demonstrates that the PV system and the BESS are connected to a DC bus. The BESS
 228 requires a CC (a DC/DC converter) to interface with the PV system because they have a different voltage.
 229 The DC bus is connected through the In (a DC/AC converter) to an AC bus exchanging electricity with
 230 the load and the grid. Figure 2 also demonstrates that some energy flows are bidirectional: batteries can be
 231 charged and discharged depending on the SHS energy balance. Furthermore, the electricity can be exported
 232 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.

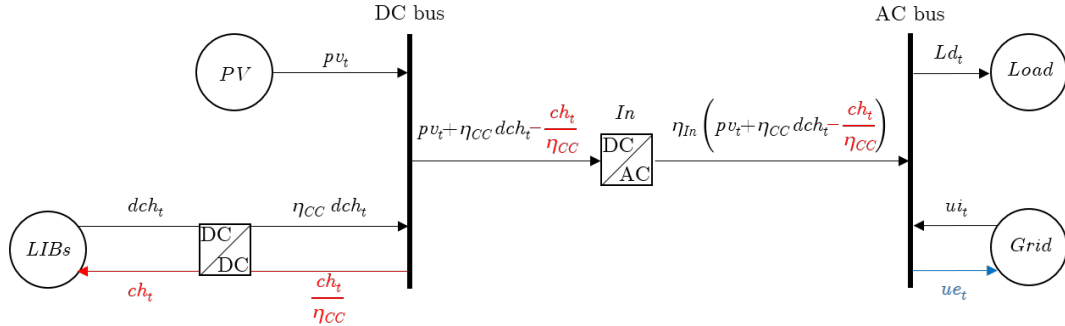


Figure 2: Graphical description of a grid-connected SHS.

233

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

240

241 for $j = 1 : n$

$$242 \quad soc_{t,j} = soc_{t-1,j} + ch_{t,j} \cdot \eta_{s,c} - \frac{dch_{t,j}}{\eta_{s,d}} \quad (5)$$

$$243 \quad MiSoc \cdot cap_{s,j} \leq soc_{t,j} \leq cap_{s,j} \quad (6)$$

$$244 \quad ch_{t,j}, dch_{t,j} \leq cap_{s,j} \cdot PCr \quad (7)$$

$$245 \quad ch_{t,j} \leq \alpha \cdot M \quad (8)$$

$$246 \quad dch_{t,j} \leq (1 - \alpha) \cdot M \quad (9)$$

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

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

$$252 \quad dch_t = \sum_{j=1}^n dch_{t,j} \quad (10)$$

$$253 \quad ch_t = \sum_{j=1}^n ch_{t,j} \quad (11)$$

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

$$260 \quad \sum_{t \in \tau_{yr}} dch_t \leq \frac{cap_s^r \bar{T}}{cap_s^r L_s} \cdot \frac{(\bar{Q} - \theta_s e^{\frac{E_a}{RK}} \sqrt{L_s}) V}{(\alpha_s K^2 + \beta_s K + \gamma_s) e^{(\delta_s K + \epsilon_s) PCr}} \quad (12)$$

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

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

$$267 \quad N^0 = \frac{1}{cap_s^r} \frac{\bar{T}}{L_s} \cdot \frac{(\bar{Q} - \theta_s e^{\frac{E_a}{RT}} \sqrt{L_s}) V}{(\alpha_s K^2 + \beta_s K + \gamma_s) e^{(\delta_s K + \epsilon_s) PCr}} \quad (13)$$

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

$$269 \quad \sum_{t \in \tau_{yr}} dch_t \leq cap_s \cdot N^0 \quad (14)$$

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

279
 280 for $j = i : n$

$$281 \quad N_j^0 = \frac{1}{cap_s^r} \frac{\bar{T}}{L_s} \cdot \frac{(\bar{Q} - \theta_s e^{\frac{E_a}{RT}} \sqrt{L_s}) V}{k_j (\alpha_s K^2 + \beta_s K + \gamma_s) e^{(\delta_s K + \epsilon_s) PCr}}$$

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

284
 285 for $j = i : n$

$$286 \quad \sum_{t \in \tau_{yr}} dch_{t,j} \leq cap_{s,j} \cdot N_j^0 \quad (15)$$

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

$$291 \quad dch_t + \frac{ch_t}{\eta_{cc}} \leq cap_{cc} \quad (16)$$

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

293 Concerning the energy generation, the PV productivity profile (pv_t) is constrained by the environmental

294 conditions as it is calculated as the product of the capacity and the productivity of a 1 kW system (SR_t),
 295 which is typical of the installation site (17).

296

$$297 \quad pv_t \leq cap_{pv} \cdot SR_t \quad (17)$$

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

301

$$302 \quad pv_t + \eta_{cc} \cdot dch_t - \frac{ch_t}{\eta_{cc}} \leq cap_{in} \quad (18)$$

$$303 \quad Ld_t = ui_t - ue_t + \eta_{in} \cdot \left(pv_t + \eta_{cc} \cdot dch_t - \frac{ch_t}{\eta_{cc}} \right) \quad (19)$$

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

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

307

$$cap_k \leq i_k \cdot M \quad (20)$$

308 2.4. Economic and Environmental Optima comparison

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

- 311 • the SHS configuration corresponding to the minimum environmental impact (Environmental Opti-
 312 mum);
- 313 • the life cycle impact and cost of the Environmental Optimum per MWh of energy provided to the load;
- 314 • the SHS configuration corresponding to the minimum economic cost (Economic Optimum);
- 315 • the life cycle impact and cost of the Economic Optimum per MWh of energy provided to the load.

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

322 Then, the effect of the variation of the costs of technologies and of the energy tariffs on the results will
 323 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

348 of three people has been selected. In this optimization problem, the productivity profile of a 1 kW PV
349 system is required as input (17) and is calculated using TRNSYS16 [51], whose library contains Meteororm
350 [52] meteorological data and models for PV performances estimation. Concerning the BESS, all the LIBs
351 analyzed by Peters and Weil [32] and used by Rossi et al. [19, 20], are evaluated as candidates for this SHS
352 application and the same nomenclature adopted by these authors has been maintained.

353 *3.1. LCA Goal and Scope definition*

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

366 *3.2. Life Cycle Inventory*

367 The LCI of this environmental assessment is based on that one published by Rossi et al. [19, 20] about
368 the whole SHS; this inventory has been disassembled in order to get a different LCI for every element of
369 the analyzed system. Furthermore, an updated version of the database (Ecoinvent 3.4 [28]) has been used
370 to model the SHS environmental performances. Particularly, the CO of LIBs has been modelled thanks to
371 the database file provided by Peters and Weil [32] and imported in openLCA [29]; their OP don't imply any
372 environmental impact whereas the EoL processes have been carefully evaluated grounding on Huang et al.
373 [53] and Weber et al. [54] studies. Concerning the PV system, the In and the CC, their CO was modelled
374 directly using Ecoinvent 3.4 [28] processes; similarly to the BEES no burdens occur during the OP whereas
375 the references for EoL are respectively Latunussa et al. [55] and Tschümperlin et al. [56]. The only impact
376 occurring during the SHS operation deals with the electricity consumption from the grid. Ecoinvent 3.4
377 provides a detailed inventory to evaluate the impact of electricity mixes, including the Italian one that was
378 used for this purpose. As Ecoinvent market processes are used, the embedded transports involved in the
379 CO, OP and EoL phases is already included in the inventory.

380 *3.3. Life Cycle Impact Assessment*

381 Similarly to Rossi et al. [19, 20], the ReCiPe Endpoint [57] calculation method has been applied with a
382 Europe H/A normalization and weighting set, aiming to evaluate results as single scores [58]. This choice

383 is particularly useful to compare in a clearer way two Product Systems including all the impact categories
 384 proposed by the LCIA method, at the price of increasing the uncertainty of the LCA model. In this study,
 385 an updated version of ReCiPe (2016) [57] compared to that used by Rossi et al. [19, 20] has been used.
 386 Indeed, this choice is necessary to compare coherently the environmental impacts of SHSs designed using a
 387 classic and an optimized approach. Furthermore ReCiPe has been used because it includes the evaluation of
 388 seventeen impact categories, being the most complete among all the LCIA methods [57].

389 3.4. Life Cycle Costing

390 Concerning the economic optimization parameters, the costs of the SHS are set grounding on a NREL
 391 [15] benchmark LCC study of a PV system. In this NREL analysis, several types of costs are accounted to
 392 calculate the total. Particularly in this paper the cost of technologies have been considered as variable and
 393 include the manufacturing expenses afforded by the producers, the profits they wants to get by selling their
 394 products and the total amount of taxes that burden on the product (including a fee for the components
 395 disposal). Contrarily the costs related to the supply chain, the installation, the marketing and permitting
 396 processes costs are supposed to be fixed. NREL provides information about the costs of two different PV
 397 systems; the first one doesn't include the BESS whereas the second one does: the LIBs costs are estimated
 398 by the difference. Nevertheless NREL considers generic LIBs cells in its benchmark analysis; Xu et al.
 399 [38] instead published a very interesting study where LIBs costs are estimated depending on the battery
 400 chemistry. Since many types of LIBs are evaluated, the costs of the cells proposed by NREL have been
 401 replaced by the costs proposed by Xu et al. [38]. Concerning the CC, as its cost is not explicitly defined in
 402 the NREL analysis but it's included in the electrical balance of system, a market component pointed out by
 403 Rossi et al. [19, 20] as a representative converter has been selected for the cost estimation [59]. Concerning
 404 the tariffs, the Italian Energy Manager [60] provides historical data about the market value of energy. The
 405 remuneration coming from the electricity exportation to the grid is equal to the energy market value, whereas
 406 taxes must be added in case of electricity withdrawal [61]. All the costs and impacts are summarized in Table
 407 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	Ah ⁻¹ K ⁻²	[16]
β	-2.998e-03	Ah ⁻¹ K ⁻¹	[16]
γ	0.446	Ah ⁻¹	[16]
δ	-6.7e-03	K ⁻¹ h	[16]
ϵ	2.35	h	[16]
θ	17127	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	Jmol ⁻¹	[16]
cap_s^r	712.9	Wh	[16]
PCr	0.3	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]

408 4. Results and discussion

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

414 4.1. Reference case

415 In this subsection, the economic and the environmental optimal designs are compared considering a
416 reference case where the input parameters assume the values listed in Table 2 and Table 3. First of all the
417 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

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

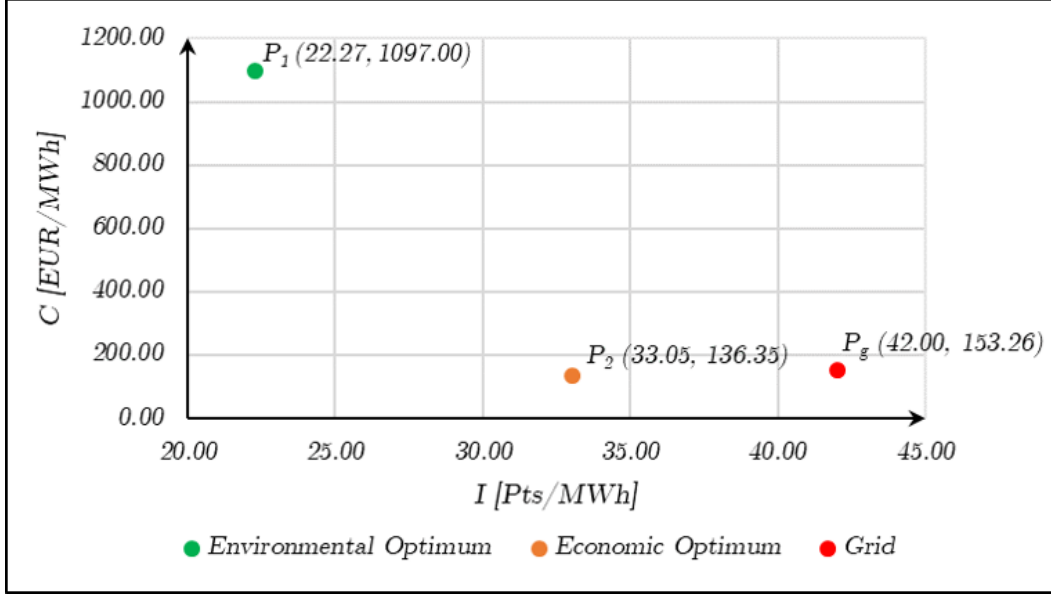


Figure 3: Graphical representation of Economic and Environmental Optima impacts and costs compared to the Italian electricity mix.

424 (12.58 kWh). According to the optimization results, M-B (NCM) batteries are identified by the model as
 425 the most sustainable LIBs for this SHS. This result partially confirms the conclusions of Rossi et al. [19,
 426 20]: indeed, although they assessed Bauer (NCA) batteries as the most sustainable technology, they stress
 427 the point that mixing cobalt and other less rare materials represents the best trade off between the batteries
 428 LCA parameters. Concerning the Economic Optimum, a battery-free PV system, whose power is 0.88 kW,
 429 is the configuration which minimizes the SHS costs. From an economic point of view, exchanging energy
 430 with the grid is more convenient than having a high self-consumption rate, which is assessed to 79% for the
 431 Environmental Optimum and 28% for the Economic one.

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

437 In their study, Rossi et al. [19, 20] calculated an environmental impact of 22.81 Pts/MWh that is slightly
 438 higher than the minimum environmental impact calculated in this study; nevertheless Rossi et al. [19,
 439 20] considered a physical allocation to evaluate the environmental benefits coming from the exportation of
 440 electricity to the grid. As underlined in the methodological section, the use of allocation in the optimization
 441 problem would lead to a non-linear cost function, but an allocation can be done afterwards to compare the
 442 results with those evaluated by Rossi et al. [19, 20]. Indeed, multiplying the results by the allocation factor
 443 $A = RF/(EE + RF)$, a minimum environmental impact of 16.52 Pts/MWh is calculated (about 30% lower

444 than Rossi et al. [19, 20]). Figure 3 also allows to compare the Environmental and the Economic Optima
445 with a benchmark case, where the user is supplied by the utility. According to the results, the burden of
446 the Environmental Optimum is lower than the impact of the electricity mix (53%), whereas its cost is much
447 higher (7.16 times the energy costs). Concerning the Economic Optimum, the environmental impact and
448 the cost of the SHS are evaluated as about 78% and 88% of the average energy tariff. The costs of these
449 optimal configurations can be compared with those of a reference SHS described in an annual report focused
450 on leveled cost of energy sources [62]: even though specific data for Italy are not available in literature,
451 this report proposes a range of values that a battery assisted PV installation can present. These costs vary
452 from 412 to 736 EUR/MWh and are between those of the economic and the environmental optima. For all
453 these reasons, it is possible to conclude that the Economic Optimum is in general more sustainable than
454 the grid whereas the economic impact represents a very critical value for the Environmental Optimum. The
455 interpretation of these results leads to the conclusion that mitigating the environmental impact of a SHS
456 moving from the Economic to the Environmental Optimum by the use of ESSs is quite expensive from an
457 economic point of view. For such reason, in the next section we'll try to mitigate the environmental impact
458 of the Economic Optimum by the variation of cost parameters.

459 4.2. Sensitivity Analysis

460 The results evaluation brought to the conclusion that optimized LCA is effective to minimize the SHS
461 impact as the Environmental Optimum is more sustainable than the Economic Optimum and than the grid,
462 but its costs are much higher. Both the Economic Optimum costs and impacts instead are lower compared
463 to the grid. Consequently we can conclude that the two optimal designs are very far from them but in
464 the future the costs of technologies and the energy tariffs may change significantly and the results might
465 be affected by this change. Applying economic optimal design to the scenarios proposed in Table 1, the
466 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

467 Analysing the SHS economic optimal designs it's possible to point out that a breakdown of the costs of
468 technologies is the only case where BEES becomes economically profitable; indeed, in Scenario H an ESS
469 with relevant capacity is included in the economic optimal design. Another observation is that, because of

470 the lower cost of the materials, the battery type minimizing the SHS cost in this scenario is Bauer (LTO),
 471 differently from the environmental optimal design where M-B (NCM) is assessed as the most sustainable
 472 LIB. Thus the SHSs cross-analysis allows to conclude that, in this scenario, the choice of the BESS depends
 473 on the rationality adopted designing the SHS.

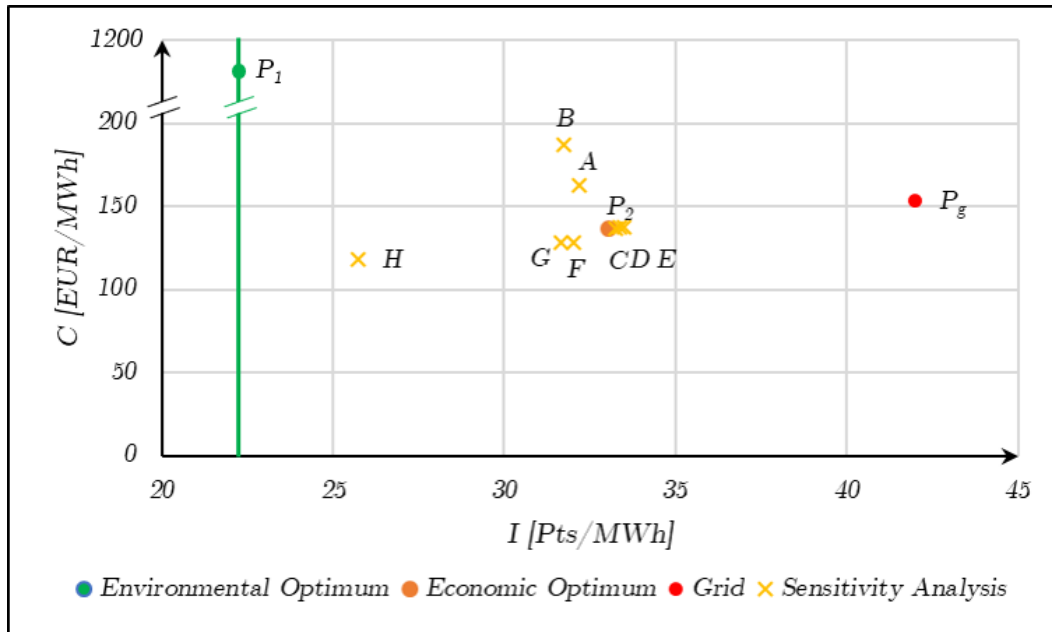


Figure 4: Graphical representation of the sensitivity analysis results compared to the reference case. The analysed scenarios are: A) Moderate increase of tariffs; B) Strong increase of tariffs; C) Moderate reduction of feed-in remunerations; D) Strong reduction of feed-in remunerations; E) Cancellation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

474 Figure 4 graphically demonstrates that the environmental impact calculated for the SHS economic optimal
 475 configuration in Scenario H is the closest to the minimum, which results from the environmental optimal
 476 design and is represented by a green line in Figure 4. Indeed, its environmental impact is 25.72 Pts/MWh,
 477 about 20% less than the Reference case, whereas the Environmental Optimum and the grid have an impact of
 478 22.27 Pts/MWh and 42.00 Pts/MWh respectively. Concerning the economic considerations, the Economic
 479 Optimum in scenario H has a cost of 117.95 EUR/MWh, lower than the Reference case (136.35 EUR/MWh)
 480 and the grid electricity (153.26 EUR/MWh). This is due to the positive effect of producing and storing
 481 energy with very low cost PV modules and LIBs. Contrarily, other less optimistic scenarios do not allow a
 482 significant environmental impact mitigation. Increasing the energy tariffs and revenues is slightly effective
 483 to lower the SHS environmental impact, whereas decreasing the revenues from the injection to the grid is
 484 assessed to increase the environmental impact.

485 5. Conclusions

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

502 6. Supporting Information

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

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