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# Optimal sizing of a Hybrid Renewable Energy System: importance of data selection with highly variable renewable energy sources

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# Abstract

The replacement of fossil fuels for producing energy with renewable sources is crucial to limit the climate change effects. However, the unpredictable nature of renewables, like sun and wind, complicates their integration within the power systems. This problem can be faced with the introduction of Hybrid Renewable Energy Systems (HRESs) where several energy sources can be incorporated. A key aspect is the assessment of the HRES configuration, which is fundamental to obtain a feasible system from both technical and economic points of view. In this paper, a novel Mixed Integer Linear Programming (MILP) optimization algorithm has been developed to design a tool capable of assessing the optimal sizing of a HRES. The algorithm has been applied to a real case study of a mountain hut located in South-Tyrol (Italy) with a hybrid system composed by solar, wind and diesel generators together with a battery storage. The algorithm compares several scenarios providing the optimal configurations of the HRES, which are characterized by different costs and energy deficits. This tool helps engineers to identify the best trade-off between costs and energy deficits in the planning phase of a HRES, still granting the demand of the users as well as the constraints.

*Keywords:* Hybrid Renewable Energy Systems, Mixed Integer Linear Programming, Solar Energy, Wind Energy, Diesel Engine, Battery Storage.

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# Nomenclature

### **PV** system

- $\alpha$  Absorptivity of the cell [-]
- $\beta$  Efficiency loss coefficient of the solar cell [°C<sup>-1</sup>]
- $\eta_{\text{BOS}}$  Balance of system efficiency [-]
- $\eta_{\rm c}$  Cell efficiency [-]
- $\eta_{n,c}$  Rated efficiency of the cell in STC [-]
- au transmissivity of the cell [-]
- $A_{\rm eff}$  Net cell opening area [m<sup>2</sup>]
- $E_{PV}$  Energy delivered by the PV system [kWh]
- G Global Irradiance on the panel tilted surface [kWh/m<sup>2</sup>]
- NOCT Nominal Operating Cell Temperature of the PV panel [°C]
- $T_{\rm A}$  Ambient temperature [°C]
- $T_{\rm C}$  Cell temperature [°C]

# Wind turbine system

 $\rho_{air(STC)}$  Air density in STC [kg/m<sup>3</sup>]

- $\rho_{air}$  Air density [kg/m<sup>3</sup>]
- $E_{WT}$  Energy delivered by the wind system [kWh]
- $P_R$  Rated power delivered by the wind turbine in STC [kW]
- $P_{WT(STC)}$  Power delivered by the wind turbine in STC [kW]
- $P_{WT}$  Power delivered by the wind turbine [kW]

 $W_{cut-in}$  Cut in speed of the wind turbine [m/s]

 $W_{cut-out}$  Cut out speed of the wind turbine [m/s]

 $W_{hub}$  Wind speed at hub height [m/s]

- $W_h$  Wind speed measured at the anemometer height [m/s]
- $W_R$  Wind speed corresponding to the rated power [m/s]
- $z_0$  Surface roughness [m]
- $z_{hub}$  Hub height [m]

# **Diesel generator**

- $\eta_{gen}$  Efficiency of the diesel generator [-]
- $\rho_{fuel}$  Fuel density [kg/m<sup>3</sup>]
- $E_{Mot}$  Energy delivered by the Diesel generator [kWh]
- $F_C$  Fuel consumption [g/s]
- *LHV*<sub>fuel</sub> Lower Heating Value [MJ/kg]
- $P_{el}$  Electrical power [kW]
- $P_r$  Rated power [kW]

# **Battery storage**

- $\sigma$  Self discharge rate [-]
- $B_C$  Battery capacity [kWh]
- $E_{batt}$  Energy delivered or stored [kWh]

# MILP model

- $C_{Batt}$  Total NPC of a battery unit [ $\in$ ]
- $C_{PV}$  Total NPC of a PV unit [ $\in$ ]
- $C_{WT}$  Total NPC of a WT unit [ $\in$ ]

- $N_{Batt}\;$  Total number of batteries units [-]
- $N_{Diesel}$  Total number of diesel generators [-]
- $N_{PV}$  Total number of PV panels [-]
- $N_{WT}$   $\,$  Total number of wind turbines [-]  $\,$

# NPC of the HRES

 $C_{fuel}$  Fuel cost [€]

- $C_{IN}$  Initial capital cost [ $\in$ ]
- $C_{O\&M}$  Operation and maintenance cost [ $\in$ ]
- $C_R$  Replacement cost [ $\in$ ]
- $D_f$  Discount factor [-]
- *f* Inflation rate [-]
- *i* Real discount rate [-]

# Other abbreviations

- BOS Balance of System
- $E_{Load}$  Energy absorbed by the load [kWh]
- GHG Greenhouse gas
- $HRES\,$  Hybrid Renewable Energy System
- MILP Mixed Integer Linear Programming
- $NPC\;$  Net Present Cost
- STC Standard Test Conditions

#### **1** 1. Introduction

The continuous development of Renewable Energy Systems (RES) has be-2 come a key aspect in many Countries all over the World with the aim of guaran-3 teeing a clean and sustainable development, as well as to contrast the effects of 4 the climate change. Even though the replacement of fossil fuels with renewables 5 for producing energy is nowadays crucial, the use of traditional sources is con-6 tinuously increasing. In such a context, the use of non-fossil fuels is still low for 7 preventing this continuous growth [1]. One of the main reasons that limits the 8 replacement of fossil fuels with renewables is their fluctuating and unpredictable 9 nature, which complicates the integration within the power systems [2]. The 10 characteristics of solar and wind energies may lead to an excess of energy pro-11 duction that would be wasted if the balance between the load requirements and 12 the generated energy does not match. For instance, a global amount of curtailed 13 electrical energy of 940.8 billion kWh was estimated in the year 2013 [3]. 14

Locations that have few connections with the national grid, or those that have 15 not been electrified so far, are typical examples where the introduction of renew-16 ables would be crucial for decreasing the environmental burden. When consid-17 ering the electrification of rural areas through mini-grids, the lack of method-18 ologies related to the assessment of the energy needs can lead to an inefficient 19 system design. Gambino et al. [4] proposed a solution that takes into account 20 both specific needs and context conditions, characterizing a community to be 21 electrified. They developed a methodology that can be applied per each different 22 case based on data collection methods, aiming to achieve a high accurate descrip-23 tion of the electricity consumption. Hybrid Renewable Energy Systems (HRESs) 24 are currently being developed in order to exploit the sources available in a de-25 termined area instead of adopting solutions based on convectional generators or 26 power grid extensions, thus resulting in a more profitable use of these sources 27 on both environmental and economic points of view [5, 6]. HRESs are outlined 28 by different configurations: for instance, they can be composed by photovoltaic 29 (PV) panels coupled with batteries [7], wind turbines paired with batteries [8], PV 30 panels mated with wind turbines [9] or by coupling PV panels and wind turbines 31 together with a Pumped Hydro Energy Storage (PHES) [10]. In addition, other 32 configurations can be PV-wind-battery [11, 12], PV-wind-hydrogen [13], PV-33 wind-battery-diesel generator [14], PV-Wind-Combined Heat and Power (CHP) 34 [15], PV-wind-biomass [16] and PV-biogas generator-PHES with battery storage 35 [17]. Further examples can be found in [18]. 36

<sup>37</sup> When considering the installation of an off-grid HRES, one of the main chal-

lenges is the evaluation of the optimal design, which is related to the selection of 38 the optimal number and size of the system components [19]. To achieve this goal, 39 optimization techniques that are divided into mathematical and metaheuristic 40 methods have to be used [20]. Mathematical methods are suitable for solving 41 linear problems and allow engineers to obtain the exact optimal solution. On 42 the other hand, metaheuristic methods find the optimal solution iteratively, thus 43 requiring lower computational efforts: however, they provide an approximate 44 solution that is not always the exact one [21]. Among the first ones, Linear Pro-45 gramming (LP) and Mixed Integer Linear Programming (MILP) have been widely 46 applied to the HRESs optimization. Morais et al. [22] used this technique to com-47 pute the optimal operation scheduling of an isolated system constituted by PV 48 panels, wind turbines and a fuel cell coupled with a storage. Ferrer et al. [23] de-49 veloped a MILP model, which has been applied to a case study in Peru, in order 50 to optimize hybrid off-grid PV-wind systems. The model computes the optimal 51 solution considering various consumption points with the aim of minimizing the 52 objective function that represents the initial investment cost of the system. Mal-53 heiro et al. [24] used a MILP model to design an isolated PV-wind-diesel with a 54 battery storage where its Levelized Cost Of Energy (LCOE) has been used as ob-55 jective function. Among the second ones, Genetic Algorithm (GA) and Particle 56 Swarm Optimization (PSO) methods have been widely employed to compute the 57 optimal sizing of HRESs. Zhao et al. [25] used a GA for a multi-objective opti-58 mization of a system composed by PV panels, wind turbines and a diesel engine 59 coupled with a battery storage. The multi-objective optimization aimed to mini-60 mize the life-cycle cost, as well as the system pollutant emissions, and maximize 61 the penetration of renewables. Stoppato et al. [26] developed a PSO model to op-62 timize the cost of a PV-PHES system in a rural village located in North Nigeria. 63 However, HRESs have been also investigated by means of commercial soft-64 ware like HOMER. For instance, HOMER has been used in [27], [28] and [29] 65 to study an off-grid PV-wind-hydro system coupled with a battery storage and a 66 back-up diesel generator, while in [30] it was used to assess the optimal planning 67 of a hybrid system composed by PV panels, diesel generators and a battery stor-68 age as well. Along the same line, the IHOGA [31] software was developed by the 69 University of Zaragoza and applies optimization models, based on GA, to anal-70 yse HRESs as discussed in [32] and [33]. In several cases, the techno-economic 71 optimization of a HRES is based on simplified assumptions that provide an opti-72 mal result but, if the external conditions vary, they can lead to either under-sized 73 or over-sized systems. The most common assumptions regard the load profile, 74 which is considered to be the same per each day of the year, and the shape of 75

<sup>76</sup> both solar and wind energies. Indeed, the selection of the optimal configuration
<sup>77</sup> of a HRES cannot be assumed as unique for an application where the daily load
<sup>78</sup> profile and the sources shape vary. For this reason, an assessment of possible
<sup>79</sup> optimal solutions can help engineers to choose the best configuration that meets
<sup>80</sup> the system needs.

In this work, a MILP optimization model has been developed with Matlab<sup>©</sup> 81 [34] and applied to a case study of a mountain hut, located in the Italian region 82 of South-Tyrol (Italy), in order to assess the optimal sizing of a PV-wind-diesel 83 generator system together coupled with a lead-acid battery storage. The paper 84 analyses the possibility of electrifying the hut through a HRES: in this case, the 85 high level of complexity related to the system optimization regards the strong 86 variability of the load, as well as the high level of fluctuations of both sun and 87 wind sources. The main novelty of the work is the methodology adopted to assess 88 how the configuration of a HRES, thus the optimal sizing, can vary depending on 89 the variability of both load and renewables, thus allowing engineers to analyse 90 several realistic cases corresponding to a specific time span. Specifically, the op-91 timization code has been run considering different possible boundary conditions 92 and the design of the system takes into account all these variations. In addi-93 tion, the effect of the reference time span selected for the optimization process 94 is studied and discussed. The MILP model also shows how the optimal output, 95 thus the sizing of the system, can change according to the parameters involved 96 in the process change, providing a complete tool that can be adapted to different 97 applications and targets. 98

The paper is structured as follows: Section 2 presents the case study, the models of the various components related to the HRES and the MILP model as well. Section 3 shows the results of the simulations and Section 4 reports the conclusions of the work.

#### **2. Research and Methods**

#### <sup>104</sup> 2.1. Problem definition and goal of the work

Most of the works available in literature that deal with the optimal sizing of the HRESs provide results in a time span of 24 hours. They are based on the shapes of both load profile and energy production from renewables. In other works [35, 36], standard hours are selected with the aim of representing the whole dataset properly, thus providing results that can be compatible and extendable to the entire time period. This strategy is particular suitable to lower the computational efforts [37] in the calculation processes. Sometimes, the daily fluctuations of the shapes of both load profile and renewable energy production do not allow engineers to choose a reference day or a significant time span to extend the results since they complicate the computation of the optimal system configuration, as well as the definition of the optimization strategy. In these cases, an assessment of the various optimal configurations, which depends on the dataset variability, is required in order to avoid a "wrong design" of the system that otherwise would not meet the real needs of the load.

The problem addressed in this paper regards the assessment of the optimal 119 sizing of a HRES where the load profile, sun and wind curves present a high 120 daily variability in a considered time period. An algorithm has been developed 121 in order to analyse the daily configuration of the system, showing how the opti-122 mization results can be significantly affected by the variability of both load and 123 renewable energies profiles. Firstly the developed model was run considering 124 each day of a specific time period and then the whole month. The main benefit 125 behind this methodology is the possibility of comparing and analysing several 126 results. Moreover, it provides a general figure of the system behavior in the con-127 sidered time period, as well as detailed information about the trend of both load 128 and renewable energy sources per each day together with the system response. 129 The goal is to provide a tool capable of depicting various configurations of a 130

HRES, thus helping engineers to assess and choose the size that best meets the
 energy demand using particular system requirements. The developed algorithm
 that has been used in the present case study is described in Subsection 2.2.

#### <sup>134</sup> 2.2. Case study

The algorithm has been applied to a case study of a mountain hut located at 135 an altitude of 2,200 m a.s.l., precisely at a latitude of  $46.819^{\circ}$  and a longitude of 136  $11.442^{\circ}$ , in South-Tyrol (Italy) that is not connected with the national grid. The 137 opening period of the hut is related to the summer season, namely from May 138 to October, and its energy needs are satisfied through a diesel generator. The 139 fuel consumption has been estimated to be about  $15,000 \ l$  per season, leading 140 to an emission of  $CO_2$  close to 10 tons. The power absorbed by the load can 141 vary significantly in the daily hours and the days as well. Figure 1 shows the 142 maximum, minimum and average power absorbed by the load per each hour of 143 the day. 144



Figure 1: Maximum, minimum and average power absorbed by the load per day

The considered area is characterized by good sun and wind sources that could potentially supply all the energy needs to the hut. However, they are also outlined by a high variability that complicates the sizing of the system. The maximum, minimum and average recorded values of the Global Irradiance on the panel tilted surface (*G*), which is expressed in  $[kWh/m^2]$ , and the wind speed, which is expressed in [m/s], are shown in Figures 2 and 3, respectively.



Figure 2: Maximum, minimum and average solar radiation per day



Figure 3: Maximum, minimum and average wind speed registered in the month of June

The data used to run the simulations have been collected through measure-151 ment campaigns and online tools. Precisely, the load profile and the wind speed 152 were recorded in June 2018 through a power meter, which was installed in the 153 main power line of the electrical control cabinet, and an anemometer. The month 154 of June has been chosen since it is the one that presents the highest number of 155 people in the hut. The data were recorded each minute in order to obtain, at 156 the end of the measurements, the hourly averaged values of the absorbed power 157 and wind speed. The global irradiance above the site in June 2018 were down-158 loaded from the Photovoltaic Geographical Information System (PVGIS) [38]. It 159 is worth noticing that the power generated, delivered or absorbed by the bat-160 tery storage has been considered constant in each time interval: therefore, the 161 produced power corresponds to the final energy production. 162

#### 163 2.3. HRES components modeling

The location where the HRES will be installed is characterized by high solar and wind sources. Therefore, the HRES will be composed by PV panels, wind and a diesel generators coupled with the battery storage. Figure 4 shows the layout of the system. Sub-subsections 2.3.1, 2.3.2 and 2.3.3 describe the mathematical model of the PV system, wind turbines system and the diesel generator, respectively, while the one related to the battery storage is assessed in Sub-subsection 2.3.4.



Figure 4: HRES layout

#### 171 2.3.1. PV system modeling

The PV system has been modeled according to [39] considering a sharp polycrystalline module [40], whose characteristics referring to Standard Test Conditions (STC) are listed in Table 1. The Direct Current DC power that is delivered by the PV system was computed through Eq. (1), where  $\eta_c$  is the cell efficiency,  $A_{\text{eff}}$  is the net cell opening area and G is the global irradiance on the panel tilted surface.

$$P_{PV-DC} = \eta_c A_{eff} G \tag{1}$$

In order to calculate the effective power delivered by the PV system, the losses related to the Balance Of System (BOS) were considered. These losses include several parameters that take into account the effective performance of the system components, such as the frequency converter, wirings, batteries, support racks and switches. The AC power delivered by the PV system is calculated through Eq. (2), considering the BOS efficiency  $\eta_{BOS}$  equal to 85%.

$$P_{PV-AC} = P_{PV-DC} \cdot \eta_{BOS} \tag{2}$$

Parameter	Value	Unit of measure
Net cell opening area $(A_{\text{eff}})$	1.47	$m^2$
Cell efficiency at STC ( $\eta_{n,c}$ )	0.14	—
Power peak	240	W
Efficiency Loss Coefficient ( $\beta$ )	0.0044	°C <sup>-1</sup>

Table 1: Characteristics of a sharp poly crystalline PV panel at STC

In this model, the performance of the panels were evaluated under real operating conditions: in particular, the effect of the temperature and the solar radiation were considered for the evaluation of the cell efficiency  $\eta_c$ , as expressed by Eq. (3):

$$\eta_{\rm c} = \eta_{\rm n,c} \left[ 1 - \beta (T_{\rm C} - 25) + 0.12 \log \frac{G}{1000} \right]$$
(3)

where  $\eta_{n,c}$  is the rated efficiency of the cell in STC,  $\beta$  is the efficiency loss coefficient of the solar cell, with increasing temperature, expressed in [°C<sup>-1</sup>], and  $T_C$ is the cell temperature. Along the same line, Eq. (4) evaluates  $T_C$ , where  $T_A$  is the ambient temperature, NOCT is the Nominal Operating Cell Temperature of the PV panel,  $\tau$  is the transmissivity of the cell and  $\alpha$  is the absorptivity.

$$T_{\rm C} = T_{\rm A} + \frac{G}{800} (NOCT - 20) \left(1 - \frac{\eta_{\rm c}}{\tau\alpha}\right) \tag{4}$$

#### <sup>193</sup> 2.3.2. Wind turbine system modeling

The power produced by a wind turbine depends on the wind speed at the 194 hub. Knowing the wind speeds, the produced power is obtained directly from 195 the power curve of the turbine supplied by the manufacturer. Generally, the 196 anemometers are located at a lower height than the hub one: therefore, Eq. (5) 197 calculates the effective wind speed considering the most used formulation for 198 heights lower than 150 m. Eq. (5) computes the values at different heights taking 199 into account the surface roughness of the installation site, whose typical values 200 are reported in [41]. 201

$$w_{hub} = w_h \cdot \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{anem}}{z_0}\right)}$$
(5)

Knowing the wind speeds at the hub height, the power output of a wind turbine is 202 computed by means of its power curve. As described by Eq. (6), the wind turbine 203 starts to generate power when the value of the wind speed reaches the cut-in 204 one  $w_{cut-in}$ . The power output increases with the increasing wind speed until its 205 rated value  $P_R$  is reached, corresponding to a wind speed  $w_R$ . Starting from  $w_R$ 206 to the cut-out speed  $w_{cut-out}$ , the power output does not increase anymore, thus 207 remaining constant and equal to  $P_R$ . Beyond the value of  $w_{cut-out}$ , the turbine 208 stops to generate power to prevent failures. Then, the power curve of a possible 209 wind turbine to be installed in the analysed site is shown in Figure 5. 210

$$P_{WT(STC)} = \begin{cases} 0, & \text{if } w_t < w_{cut-in} \text{ or } w_t > w_{cut-out} \\ P_i, & \text{if } w_{cut-in} \le w_t < w_R \\ P_R, & \text{if } w_R \le w_t \le w_{cut-out} \end{cases}$$
(6)



Figure 5: Possible power curve of a wind turbine eligible for the site of interest

It is worth noticing that the power output reported in Figure 5 considers an air density  $\rho$  of 1.225  $kg/m^3$  in STC ( $\rho_{STC}$ ). In case of a different air density, Eq. (7) corrects the power output of the wind turbine  $P_{WT}$ . In this case study, an air density of 1.007  $kg/m^3$  has been considered [42].

$$P_{WT} = P_{WT(STC)} \cdot \frac{\rho_{air}}{\rho_{air(STC)}}$$
(7)

#### 215 2.3.3. Diesel generator modeling

A diesel engine has been chosen as generator, which consists on a  $3.5 \ kW$ 216 engine described in [43]. A greater size of the generator has not been chosen due 217 to the implicit goal of maximizing the use of renewable energies. A larger gen-218 erator would have added an additional constraint to limit the power output in 219 determined cases. Certainly, this would have led to a better overall optimization, 220 but also let the generator operate outside its best efficiency range, thus lower-221 ing the performance. The fuel consumption and the efficiency curves reported 222 in [43] were used to model the power generated by the diesel engine. The fuel 223 consumption of the generator is calculated with Eq. (8), which represents the 224 fuel consumption curve of the engine fed by the diesel fuel. It depends on the 225 generated electrical power  $P_{el}$  and a binary variable  $P_g$  that assumes the value of 226 0 or 1 whether the diesel generator is turned off or on, respectively. The coeffi-227 cients  $\phi$  and  $\psi$  have been obtained through laboratory tests and their respective 228 values are equal to  $0.087 \ g/kW$  and 0.127. 229

$$F_C = \phi \cdot P_{el} + \psi \cdot P_g \tag{8}$$

Figure 6 shows the fuel consumption curve experimentally obtained in [43]. The fuel consumption is expressed in [g/s] (Y-axis) as a function of the electrical power (X-axis), which is expressed in [kW].



Figure 6: Fuel consumption curve of the diesel generator [43]

The efficiency of the diesel generator is calculated with Eq. (9), which corresponds to the ratio between the produced energy and the one provided by the fuel. The efficiency curve of the considered generator is shown in Figure 7.

$$\eta_{gen} = \frac{3.6 \cdot P_{el}}{\rho_{fuel} \cdot (F_C \cdot LHV_{fuel})} \tag{9}$$

 $_{236}$   $LHV_{fuel}$  represents the Lower Heating Value (LHV) of the fuel and  $\rho_{fuel}$  is  $_{237}$  the fuel density equal to 42.6 MJ/kg and 0.828 kg/l, respectively.



Figure 7: Efficiency curve of the diesel generator [43]

If a general motor is considered and the fuel consumption curve is not provided by the manufacturer, a simplified fuel consumption curve, which correlates
the generator rated power to the generated electrical power, can be used [44].

#### 241 2.3.4. Battery storage modeling

The battery storage in a HRES plays a key role since it stores the excess of energy produced by renewable sources, as well as to deliver it to the load during the high demand. Lead-acid batteries are chosen to model the storage. This type of battery is more suitable for climates subjected to low temperatures, which can be sometimes lower than 0 °C also in summer seasons, as it occurs in this case

study. The energy that can be delivered or stored by the batteries at each time 247 interval depends on the one that is already present in the battery  $E_{\text{batt}}$ , the self 248 discharge rate  $\sigma$  and the energy balance between the generators and the load. 249 During the discharging phases, the batteries supply the remaining energy to the 250 load. This amount of energy is evaluated by means of Eq. (10). When the energy 251 produced by the generators exceeds the load requirements, this overproduction 252 can be stored in the batteries. The amount of the stored energy is expressed 253 through Eq. (11). 254

$$E_{batt}(t) = E_{batt}(t-1) \cdot (1-\sigma) + [E_{Load}(t) - (E_{PV}(t) + E_{WT}(t) + E_{Mot}(t))]$$
(10)

$$E_{batt}(t) = E_{batt}(t-1) \cdot (1-\sigma) + [E_{PV}(t) + E_{WT}(t) + E_{Mot}(t) - E_{Load}(t)]$$
(11)

In order to simulate a real behavior of the batteries, the delivered energy cannot drop below the minimum State of Charge  $SOC_{min}$ , which is equal to the 257 20% of the batteries capacity  $B_C$ .

#### 258 2.4. MILP modeling

The Linear Programming (LP) is an optimization algorithm in which a linear 259 objective function has to be minimized or maximized with respect to a defined 260 time period and a temporal discretization through time steps. When only some 261 variables have to be integer, the problem is called Mixed Integer Linear Program-262 ming (MILP) [45]. A MILP problem consists of: i) an objective function, ii) deci-263 sion variables and iii) constraints. The target of the MILP problem is to minimize 264 an objective function choosing the best values of the decision variables that re-265 spect the established constraints. A flow chart that shows the MILP optimization 266 steps is reported in Figure 8. Objective functions, decision variables and con-267 straints that constitute the problem are described in Sub-subsections 2.4.1, 2.4.2 268 and 2.4.3, respectively. 269



Figure 8: Flow chart of the MILP optimization algorithm

# 270 2.4.1. Objective function

The objective function of the MILP algorithm is the total Net Present Cost 271 (NPC) of the system, which is the sum of the total NPC related to each element 272 that constitutes a HRES. The total cost of an element embedded in a HRES can be 273 defined as the sum of the initial capital cost  $C_{IN}$ , the operation and maintenance 274 (O&C) cost  $C_{O\&M}$  and the replacement one  $C_R$ . If the fuel is consumed, the 275 supposed quantity of the fuel consumption in the lifetime of the generator  $F_c$ 276 and its cost  $C_{fuel}$  must be included. In order to obtain the NPC, all the costs 277 must be actualized at the present stage of the project. The objective function is 278 expressed by Eq. (12). 279

$$min\left(N_{PV}C_{PV} + N_{WT}C_{WT} + N_{Batt}C_{Batt} + C_{Diesel}N_{Diesel} + F_cC_{fuel}\right) \quad (12)$$

where  $N_{PV}$ ,  $N_{WT}$  and  $N_{Batt}$  are the total number of PV panels, wind turbines and batteries units, respectively.  $N_{Diesel}$  is the number of diesel generators that in this case has been set equal to 1 and does not constitute a decision variable of this specific optimization problem. Nevertheless, it has been included in the problem in order to improve the flexibility of the algorithm when a different case study is used.  $C_{PV}$ ,  $C_{WT}$ ,  $C_{Batt}$  and  $C_{Diesel}$  are the total NPCs of a single PV panel, wind turbine, battery and diesel generator respectively.  $F_c$  and  $C_{fuel}$  are the fuel consumption of the diesel generator and the fuel cost, respectively.

#### 288 2.4.2. Decision variables

The decision variables determine the output of the objective function. The target of the MILP algorithm consists on minimizing the objective function, thus to find the values of the decision variables for reaching this target. In the analysed case, the decision variables are the following:

- $N_{PV}$ : number of PV panels;
- $N_{WT}$ : number of wind turbines;
- $N_{Batt}$ : number of batteries units;
- $E_{Batt}(t)$ : energy delivered or absorbed by the battery per each time interval;
- $E_{Dq}(t)$ : energy delivered by the diesel generator per each time interval.

### 299 2.4.3. Constraints

The constraints are mathematically expressed in form of equalities and in-300 equalities, thus limiting the values that can be attributed by the algorithm to the 301 decision variables. They are related to technological, economic or geometrical 302 limitations. In this case study, technological and geometrical constraints are in-303 volved. Eq.s (13), (14) and (15) set the technological constraints, while Eq.s (16), 304 (18) and (17) define the geometrical ones. Eq. (13) expresses the balance between 305 the energy produced by the HRES and the load demand. The produced energy 306 has to satisfy the load demand per each time interval. It is also assumed that 307 the excess of the produced energy can be managed by the inverter connected to 308 the PV modules and the pitch control system of the wind turbines, thus reduc-309 ing the power output by letting the generators operate in off-design conditions 310 according to the power curves of the machines. 311

$$E_{Load}(t) \le E_{PV}(t)N_{PV} + E_{WT}(t)N_{WT} + E_{Dg}(t) + E_{Batt}(t)$$
(13)

Eq.s (14) and (15) limit the energy that can be delivered or absorbed by the battery storage per each time interval. Eq. (14) sets both lower and upper limits of the energy delivered by the batteries per each time interval, thus establishing that the energy delivered by the batteries cannot be lower than the minimum State Of Charge  $(SOC_{min})$ , which corresponds to 20% of the battery capacity  $(B_C)$ . In addition, the maximum energy delivered per each time interval cannot exceed the SOC of the batteries, i.e. the effective amount of energy left in the batteries after their operation in the previous time interval.

$$SOC_{min} \cdot B_C \cdot N_{Batt} \le E_{Batt-out}(t) \le SOC(t-1) \cdot B_C \cdot N_{Batt}$$
 (14)

$$E_{Batt-in}(t) \le B_C \cdot N_{Batt} - SOC(t) \cdot B_C \cdot N_{Batt}$$
(15)

Eq. (16) limits the available ground area of the wind turbines in the installation site: precisely,  $S_o$  is the one occupied by a wind turbine. It is worth noticing that the total area that can be occupied by the wind turbines  $N_{WT} \cdot S_o$  cannot exceed the available area S<sub>a</sub>.

$$N_{WT} \le \frac{S_a}{S_o} \tag{16}$$

Eq. (17) limits the ground area that can be occupied by PV panels: namely, L and l are the larger and the smaller sides of the available ground area, respectively, a is the smaller side of the PV module, c is the projection of the larger side b of the panel on the ground and d is the distance between the rows of the PV panels. A clear description of these geometrical parameters is shown in Figure 9.

$$N_{PV} \le \frac{L \cdot l}{a \cdot (c+d)} \tag{17}$$



Figure 9: Dimensions of the PV panels

Eq. (18) reports the calculation process used to obtain the constraints deriving by Eq. (17).

$$\begin{cases} N_{PV} \leq \frac{l}{a} \cdot N_{rows} \\ N_{rows} = \frac{L}{c+d} \\ c = b \cdot \cos(\beta) \\ d = k \cdot \sin(\beta) \\ k = \frac{1}{\tan(61^{\circ} - Latitude)} \end{cases}$$
(18)

where  $\beta$  is the tilt angle of the PV panel, *b* is the larger side of the PV module and *k* is a coefficient used to calculate the distance between two PV panels rows, which depends on the latitude where they are installed. Table 2 lists the values of the parameters used to limit the ground areas occupied by the PV panels and the wind turbines.

Parameter	Value	Unit of measure
$S_a$	100	$m^2$
$S_o$	25	$m^2$
L	10	m
l	10	m
a	0.994	m
b	1.652	m
$\beta$	30	degrees
Latitude	46.819	degrees

Table 2: Parameters adopted to limit the ground areas of PV panels and wind turbines

# 337 2.5. Economic analysis - NPC of the HRES

The MILP algorithm computes the optimal solution of the problem finding 338 the values of the optimization variables that minimize the objective function, 339 which is the minimum NPC of the system. Generally, the NPC of an investment 340 allows the investors to choose the optimal option among different ones. The NPC 341 is defined as the sum of the present value of all the costs minus the sum of the 342 present value of all the benefits. Therefore, the NPC of a component considers 343 its total cost that is composed by the initial capital cost  $C_{IN}$ , the operation and 344 maintenance (O&M) cost  $C_{O\&M}$ , the replacement cost  $C_R$  and, eventually, the 345

fuel cost  $C_{fuel}$  taking into account the Time Value of Money (TVM) through a discount factor  $D_f$ . For sense of clarity,  $D_f$  is used to calculate the present value of the cash flow during the project lifetime and it is defined by Eq. (19).

$$D_f = \frac{1}{\left(1+i\right)^n} \tag{19}$$

Referring to Eq. (19), i is the real discount rate, which takes into account the money inflation as defined by Eq. (20), and n is the lifetime of the project expressed in years.

$$i = \frac{i_{nom} - f}{1 + f} \tag{20}$$

Referring to Eq. (20),  $i_{nom}$  represents the nominal discount rate that indicates the rate at which money can be borrowed, while f is the expected inflation rate.  $D_f$  decreases over the years, thus stating that a future cash flow is less worth than a present one. Considering an expected inflation rate of about 2%,  $D_f$  has been considered equal to 6%.

## 357 3. Results and comments

The goal of the work is to demonstrate that the choice of the dataset used to run the simulation has a crucial role on the results: therefore, all the outcomes of the calculations require a correct evaluation to avoid misunderstandings. In particular, simulations aim to show how the optimal solution varies depending on the assumptions made on the renewable energy sources profiles. The MILP optimization algorithm was used taking into account three different cases related to the HRES:

• **Case** 1: The simulation was run considering a time span of 24 hours. In this 365 case, it is possible to analyse how the configuration of the HRES changes 366 depending on the fluctuations of the power absorbed by the load and the 367 power produced by the renewable sources as well. This case is important 368 for analysing how the variability of the dataset can affect the optimal solu-369 tion. The reduction of the Greenhouse gases (GHGs) emissions derived by 370 feeding the load with the HRES instead of only a diesel generator is also 371 shown. 372

• **Case** 2: The simulation was run considering a time span of 1 month. In this case, the output of the analysis is a unique configuration that meets

the constraints per each hour of the month, thus satisfying the load re-375 quirements. Furthermore, it is the most robust solution, but also the most 376 expensive. Indeed, the system will be oversized and the excess of the pro-377 duced energy will be managed by the PV inverter and the pitch control 378 system of the wind turbines that can shift the operating point of PV panels 379 and wind turbines, respectively, to off-design conditions accordingly to the 380 required power output regulation. Also in this case, a reduction of GHGs 381 emissions is presented. 382

• Case 3: The simulation was run considering a time span of 24 hours, vary-383 ing the constraint of the load requirements from 100% of the actual value to 384 50%, with steps of 10%. Indeed, it can be supposed that it is not always nec-385 essary to satisfy the total hourly load described by the load profile curves, 386 applying a demand side management strategy. In these cases, a percent-387 age of the load can be sometimes sacrificed since it is not essential. For 388 instance, loads like a cold storage can hold some hours without the elec-389 trical supply. This case aims at demonstrating that a reduced percentage 390 of the load requirements lowers the dependency on the renewable energy 391 sources profiles, thus reducing the variability of the total NPC between the 392 most expensive and the cheapest solutions. As a result, the algorithm helps 393 engineers to reduce the total cost of the system, adopting a configuration 394 that is not oversized over the entire time period. Furthermore, a sensitivity 395 analysis has been performed in order to assess the effects of fuel and bat-396 tery prices variations. Simulations have been run considering a fuel price 397 variation from  $1.4 \in l$  to  $3.8 \in l$ , with steps of  $0.2 \in l$ , and a decreasing 398 battery price with steps of 5% until the 50% of its actual cost per kWh is 399 reached. This wide fuel price variation has been chosen to better point out 400 how the fuel price variation affects the HRES optimal sizing. For sense of 401 clarity, diesel prices can vary from  $1.4 \in l$  in developing countries to  $3 \in l$ 402 in remote areas characterized by a complicate fuel distribution system [46] 403 and [47]. 404

Per each case, an economic analysis based on the NPC has been carried out. The
economic parameters used in the simulation are described in Table 3.

PV panels	$C_{IN}$ $C_{O\&M}$	$\begin{array}{c}1,400\\0.081\end{array}$	$e/kW \\ e/kW(daily)$
Wind turbines	$\begin{array}{c} C_{IN} \\ C_{O\&M} \end{array}$	$2,000 \\ 0.095$	$\begin{array}{l} \mathbf{e}/kW \\ \mathbf{e}/kW(daily) \end{array}$
Batteries	$C_{IN} \\ C_{O\&M} \\ C_R$	$1,223 \\ 0.1 \\ 612$	$\begin{array}{l} \mathbf{c}/kWh \\ \mathbf{c}/kWh(daily) \\ \mathbf{c}/kWh \end{array}$
Diesel generator	$C_{IN} \\ C_{O\&M} \\ C_{fuel}$	$550 \\ 438 \\ 2$	$\begin{array}{c} \mathbf{E}/kW \\ \mathbf{E}/year \\ \mathbf{E}/l \end{array}$

Table 3: Economic parameters used to run the simulation [44, 48, 49, 50, 51]

#### 407 3.1. Case 1 and case 2

Results of the first two cases are presented in Table 4. The MILP algorithm computes the optimal number of PV panels, wind turbines and battery units that minimizes the total NPC of the system per each day related to the considered time interval. The algorithm also computes the value of the energy delivered or absorbed by the batteries, thus optimizing the energy produced by the generators and minimizing the effect of the fluctuating renewable energy sources.

Table 4 lists the results obtained in Cases 1 and 2, showing that the optimal 414 size of the system varies over the considered days and highlighting a noticeable 415 difference between the solution characterized by the highest and the lowest NPC. 416 Results also show that the variability of the power absorbed by the load and 417 the fluctuating nature of both sun radiation and wind speed strongly affects the 418 output of the simulation. Moreover, it can be noticed how the results of the sim-419 ulation change according to the considered time span. When considering a time 420 span of 24 hours, the algorithm sizes the system in order to optimize the energy 421 produced by renewable energy sources, reducing the fuel consumption of the 422 diesel generator and considering also the energy stored in the battery storage 423 during the night hours when the sun radiation cannot contribute to the energy 424 supply. As a consequence, the battery storage is completely discharged at the 425 end of the day, contributing to a lower sizing and, eventually, to the impossi-426 bility of meeting the power demand if the first hours of the following day are 427 characterized by low values of wind speeds. The simulation over the time span 428 of the entire month (Case 2), as shown in the last line of Table 4, considers the 429

worst scenario in which there is a lack of both solar and wind production in the 430 different days: therefore, the result presents a bigger capacity of the battery stor-431 age. Figures 10 and 11 show the simulation results considering the time period of 432 the  $7^{th}$  and the  $17^{th}$  of June 2018, respectively. These two days were selected in 433 order to highlight the behavior of the system when dealing with a different load 434 and with variable profiles of the sun radiation and the wind speed. It is worth 435 noticing that the negative values in the battery power profile indicate the periods 436 of the day during which the battery is charged, while the positive values refer 437 to the supply of power from the battery, namely the discharge phase. In the first 438 case, the optimal solution computed by the algorithm does not include the wind 439 turbines due to the lack of the wind source. The algorithm computes the optimal 440 solution relying significantly on the contribution of the diesel generator during 441 the daily hours characterized by a lack of the sun source. In the second case, the 442 optimal solution computed by the optimization algorithm includes the exploita-443 tion of the wind source and a minimum contribution of the diesel generator is 444 required. In this case, the HRES is able to satisfy the load requirements relying al-445 most entirely on renewable energy generators and batteries. In both cases, it can 446 be noticed how the PV production and the batteries operations are complemen-447 tary. The system aims to charge the batteries with the excess of PV production 448 to use them when renewable resources cannot be exploited. For sense of clarity, 449 it is worth noticing that the trend of the energy supplied by the PV system does 450 not correspond exactly to the one reported in Figure 2 since a control system is 451 implemented to modulate the power delivered through the solar inverter. Sim-452 ilarly, the wind turbine includes a pitch control functionality to modulate the 453 generated power when an excessive power production is achieved. Figure 12 454 shows the trend of the load profile, the energy produced by the HRES and the 455 SOC of the batteries in the entire month. It is worth noticing that the diesel gen-456 erator operates when the energy cannot be supplied by both PV panels and wind 457 turbines, thus operating at its rated power to optimize the fuel consumption. The 458 diesel generator does not operate when solar and wind sources are abundant. In 459 this case, the entire energy needs are supplied by PV panels, the wind turbine 460 and the battery storage, either supplying energy when needed or absorbing its 461 overproduction. It can be also appreciated how a change of the simulation time 462 span from 24 hours to the entire month affects the simulation results related to 463 each single day computed in a scenario of 24 hours. For instance, considering 464 the  $7^{th}$  of June, the optimization algorithm has to compute the charge/discharge 465 operation of the battery pack and the power delivered by the diesel generator in 466 a day taking into account the previous operating conditions and the state of the 467

# <sup>468</sup> HRES. Therefore, results shown in Figures 10 and 12 differ one to each other.

Table 4: Comparison between different configurations of the HRES. Case 1 (results of each single day) and Case 2 (results of the whole month)

Day	$N_{PV}$	$N_{WT} \\$	Battery [kWh]	NPC <sub>tot</sub> [€]	NPC <sub>PV</sub> [€]	NPC <sub>WT</sub> [€]	NPC <sub>Bat</sub> [€]	NPC <sub>Mot</sub> [€]
1 <sup>st</sup> June	103	0	12	169,720	44,523	0	35,573	89,624
2 <sup>nd</sup> June	119	0	20	152,967	51,439	0	59,288	42,240
3 <sup>rd</sup> June	138	0	16	167,448	59,652	0	47,430	60,366
4 <sup>th</sup> June	169	0	21	151,011	73,052	0	62,252	15,706
5 <sup>th</sup> June	146	0	21	148,444	63,110	0	62,252	23,082
6 <sup>th</sup> June	89	0	17	103,946	38,471	0	50,395	15,080
7 <sup>th</sup> June	63	0	8	122,607	27,232	0	23,715	71,659
8 <sup>th</sup> June	93	0	12	147,277	40,200	0	35,573	71,504
9 <sup>th</sup> June	182	0	17	182,475	78,672	0	50,395	53,409
10 <sup>th</sup> June	74	0	8	98,311	31,987	0	23,15	42,608
11 <sup>th</sup> June	1	2	15	175,084	432	49,397	44,466	80,788
12 <sup>th</sup> June	72	0	8	125,813	31,123	0	23,715	70,975
13 <sup>th</sup> June	50	1	7	92,858	21,613	24,699	20,751	25,796
14 <sup>th</sup> June	105	0	17	176,568	45,387	0	50,395	80,786
15 <sup>th</sup> June	75	1	4	94,895	32,420	24,699	11,858	25,919
16 <sup>th</sup> June	189	1	13	160,185	81,697	24,699	38,537	15,251
17 <sup>th</sup> June	126	1	14	137,282	54,465	24,699	41,502	16,617
18 <sup>th</sup> June	73	1	5	86,342	31,555	24,699	14,822	15,266
19 <sup>th</sup> June	29	2	6	94,260	12,536	49,397	17,786	14,541
20 <sup>th</sup> June	60	0	22	150,473	25,936	0	65,217	59,321
21 <sup>st</sup> June	77	0	24	120,933	33,284	0	71,145	16,504
22 <sup>nd</sup> June	48	1	6	97,159	20,749	24,699	17,786	33,926
23 <sup>rd</sup> June	57	0	16	115,275	24,639	0	47,430	43,206
24 <sup>th</sup> June	74	0	18	129,388	31,987	0	53,359	44,041
25 <sup>th</sup> June	46	2	18	130,500	19,884	49,397	53,359	7,860
26 <sup>th</sup> June	49	2	4	115,954	21,181	49,397	11,858	33,518
27 <sup>th</sup> June	35	1	0	47,688	15,129	24,699	0	7,860
28 <sup>th</sup> June	26	1	4	82,272	11,239	24,699	11,858	34,477
29 <sup>th</sup> June	27	2	3	84,371	11,671	49,397	8,893	14,409
30 <sup>th</sup> June	106	2	23	171,258	45,820	49,397	68,181	7,860
Month	110	1	10	171,473	47,549	24,699	29,644	69,851



Figure 10: Simulation results of the 7<sup>th</sup> June 2018



Figure 11: Simulation results of the 17<sup>th</sup> June 2018



Figure 12: Load profile and contribution of the HRES over a month

Table 5 shows the GHGs emissions in terms of  $CO_2$  and  $NO_x$  due to the electrical energy provided by the diesel generator. It also provides a comparison between the total GHGs emissions if the load would be entirely satisfied by the diesel generator. It is worth noticing the remarkable reduction due to the introduction of the renewable energy technologies in the energy system.

Day	El. Energy		NO <sub>x</sub>	CO <sub>2</sub> diesel	NO <sub>x</sub> diesel	CO <sub>2</sub>	NO <sub>x</sub>
	Delivered [kwh]	[ĸg]	[ĸg]	only [kg]	only [kg]	savings %	savings %
1 <sup>st</sup> June	31.3	71	0.38	33	1.74	79	79
2 <sup>nd</sup> June	12.9	32.2	0.17	330	1.72	90	90
3 <sup>rd</sup> June	19.8	48	0.25	332	1.73	86	85
4 <sup>th</sup> June	2.8	8.3	0.04	307	1.59	97	97
5 <sup>th</sup> June	5.4	16.4	0.09	296	1.53	94	94
6 <sup>th</sup> June	2.5	8.5	0.04	284	1.48	97	97
7 <sup>th</sup> June	24.5	55.2	0.29	297	1.53	81	81
8 <sup>th</sup> June	24.4	55.2	0.29	293	1.52	81	81
9 <sup>th</sup> June	17.5	39.4	0.21	324	1.68	88	88
10 <sup>th</sup> June	13.1	32.1	0.17	369	1.91	91	91
11 <sup>th</sup> June	28	63.1	0.34	301	1.56	79	79
12 <sup>th</sup> June	24.1	55.4	0.29	319	1.65	83	82
13 <sup>th</sup> June	6.8	15.8	0.08	310	1.61	95	95
14 <sup>th</sup> June	28	63.1	0.34	294	1.53	79	78
15 <sup>th</sup> June	6.9	15.8	0.08	336	1.75	95	95
16 <sup>th</sup> June	2.6	8.4	0.04	340	1.77	98	98
17 <sup>th</sup> June	3.3	8	0.04	364	1.89	98	98
18 <sup>th</sup> June	2.6	8.4	0.04	364	1.90	98	98
19 <sup>th</sup> June	2.2	8.6	0.04	337	1.76	97	98
20 <sup>th</sup> June	19.2	48.3	0.25	345	1.80	86	86
21 <sup>st</sup> June	3.2	8	0.04	343	1.79	98	98
22 <sup>nd</sup> June	9.8	24.1	0.13	367	1.91	93	98
23 <sup>rd</sup> June	13.4	31.9	0.17	364	1.90	91	91
24 <sup>th</sup> June	13.8	31.6	0.17	398	2.08	92	92
25 <sup>th</sup> June	0	0	0	386	2.02	100	100
26 <sup>th</sup> June	9.6	24.2	0.13	340	1.77	93	93
27 <sup>th</sup> June	0	0	0	356	1.86	100	100
28 <sup>th</sup> June	10.1	23.9	0.13	350	1.83	93	93
29 <sup>th</sup> June	2.1	8.6	0.04	376	1.96	98	98
30 <sup>th</sup> June	0	0	0	385	2.01	100	100
Month	678	1,710	25	10,138	52.8	83	52

Table 5: GHGs emissions savings

# 474 3.2. Case 3

Table 6 refers to Case 3 and provides the values of the minimum and the maximum NPC, as well as the difference between them whether a hourly energy deficit is accepted. It is worth noticing that, reducing the percentage of the total hourly load, the difference between the maximum and the minimum NPC

 $_{479}$  decreases down to 57%.

% of load demand to satisfy	Min NPC [€]	Max NPC [€]	Max - Min NPC [€]	% of the decrease
100%	47,688	182,475	134,787	_
90%	44,662	165,088	120, 426	11~%
80%	42,501	147,645	105, 144	22~%
70%	40,339	130,639	90,300	33~%
60%	38,178	113,005	74,827	44 %
50%	37,252	95,863	58,611	57~%

Table 6: Minimum and maximum NPCs from different configurations with demand management

Table 7 lists the results obtained in a time span of 24 hours, considering a 480 decreasing battery price with steps of 5% until a drop of 50% is achieved, corre-481 sponding to a battery price of  $581 \in /kWh$ . Table 7 highlights how a reduction 482 of the battery price affects the number of PV panels, wind turbines, battery units 483 and the NPCs of both HRES and diesel generator. It can be noticed how a reduc-484 tion of the battery price leads to an increase of the battery units until their price 485 drops to 50%. Precisely, the most expensive solution occurs for the simulation 486 of the  $16^{th}$  of June, while the cheapest is obtained for the  $9^{th}$  of June. The need to 487 exploit the sun source, coupled with a consistent reduction of the battery price, 488 leads to an increase of the PV units so that the battery cost becomes competi-489 tive with respect to the PV one. Considering the diesel generator, its total NPC 490 slightly increases when the battery price decreases of 10%, which corresponds 491 to  $1,040 \in kWh$ , since the generator is preferred than the PV panels: for this 492 reason, the cost of the diesel generator decreases until to 7,860  $\in$  since it is only 493 used as a backup. 494

Battery Price [€/kWh]	PV panels Max   Min	Wind turbines Max   Min	Battery units Max   Min	NPC Generator [€] Max   Min	NPC HRES [€] Max   Min
1,223	$182 \mid 35$	0   1	17   0	$53,409 \mid 7,860$	182,475   47,688
1,162	182 35	0   1	$17 \mid 0$	$53,409 \mid 7,860$	179,962   47,688
1,101	$151 \mid 35$	0   1	$22 \mid 0$	$53,432 \mid 7,860$	177,415   47,688
1,040	$145 \mid 29$	0   1	23   1	$53,389 \mid 7,860$	$174,045 \mid 47,615$
978	$145 \mid 29$	0   1	23   1	$53,389 \mid 7,860$	$170,589 \mid 47,465$
917	$141 \mid 29$	0   1	24   1	$52,862 \mid 7,860$	$167,155 \mid 47,317$
856	$142 \mid 29$	0   1	41   1	$16,800 \mid 7,860$	$163,329 \mid 47,169$
755	$144 \mid 29$	0   1	45   1	$7,860 \mid 7,860$	$142,457 \mid 46,924$
697	$144 \mid 25$	0   1	45   2	$7,860 \mid 7,860$	$146, 130 \mid 46, 744$
639	$144 \mid 25$	0   1	45   2	$7,860 \mid 7,860$	$139,804 \mid 46,463$
581	$205 \mid 25$	0   1	29   2	$7,860 \mid 7,860$	$137,314 \mid 46,182$

Table 7: Results obtained considering a decreasing battery price

Table 8 shows the results obtained after a sensitivity analysis performed on 495 the diesel price, considering the most expensive and the cheapest system config-496 uration. An increasing diesel price with steps of  $0.2 \in l/l$  has been considered, 497 starting from a value of  $1.4 \in /l$  to a value of  $3.8 \in /l$ . When dealing with the 498 most expensive solution, an increase of the diesel price from 1.4 to 1.6  $\in/l$  leads 499 to a consistent increase of the number of PV panels and battery units. Then, their 500 number remains stable until a value of 2.4  $\in/l$  is reached. This occurs in the day 501 characterized by the most expensive configuration changes from the  $9^{th}$  to the 502  $14^{th}$  of June during which the HRES configuration is the same also with a diesel 503 price of 2.8  $\in/l$ . This is due to the fact that, considering a diesel price that varies 504 from 1.6  $\in/l$  to 2.8  $\in/l$ , the increase does not affect the competitiveness of the 505 diesel generator with respect to the other generators. This is also demonstrated 506 by the fact that the total NPC of the system grows progressively. Moving from 507 2.8 €/*l* to 3 €/*l*, the algorithm favors a solution constituted by a higher number 508 of battery units and the diesel generator, where the former does not contribute 509 to the load energy needs. This is demonstrated by the fact that the total NPC of 510 the system remains constant. 511

Fuel Price [€/l]	PV panels Max   Min	Wind turbines Max   Min	Battery units Max   Min	NPC HRES [€] Max   Min	Day of June Max   Min
1.4	169   35	0   1	$6 \mid 0$	167,261   47,688	$9^{th} \mid 27^{th}$
1.6	182   35	0   1	17   0	173, 365   47, 688	$9^{th} \mid 27^{th}$
1.8	$182 \mid 35$	0   1	$17 \mid 0$	177,920   47,688	$9^{th} \mid 27^{th}$
2.0	$182 \mid 35$	0   1	$17 \mid 0$	182,475   47,688	$9^{th} \mid 27^{th}$
2.2	$182 \mid 35$	0   1	$17 \mid 0$	187,030   47,688	$9^{th} \mid 27^{th}$
2.4	$182 \mid 35$	0   1	$17 \mid 0$	191, 585   47, 688	$9^{th} \mid 27^{th}$
2.6	$105 \mid 35$	0   1	$17 \mid 0$	198,445   47,688	$14^{th}   27^{th}$
2.8	$105 \mid 35$	0   1	$17 \mid 0$	205,738   47,688	$14^{th} \mid 27^{th}$
3.0	$105 \mid 35$	0   1	$52 \mid 0$	207, 396   47, 688	$14^{th} \mid 27^{th}$
3.2	$105 \mid 35$	0   1	$52 \mid 0$	207, 396   47, 688	$14^{th} \mid 27^{th}$
3.4	$105 \mid 35$	0   1	$52 \mid 0$	207, 396   47, 688	$14^{th} \mid 27^{th}$
3.6	$105 \mid 35$	0   1	$52 \mid 0$	207, 396   47, 688	$14^{th} \mid 27^{th}$
3.8	205   35	0   1	$52 \mid 0$	207, 396   47, 688	$14^{th} \mid 27^{th}$

Table 8: Simulation results with a decreasing fuel price

#### 512 4. Conclusions

A MILP algorithm has been developed with the aim of analysing how the 513 choice of the reference dataset for designing a HRES can strongly affect the opti-514 mal configuration due to the strong variability of the renewable energy sources. 515 The algorithm was used considering a case study of a mountain hut located in 516 South-Tyrol (Italy) at an altitude of 2,200 m a.s.l. where the national power grid 517 is not present. The applied methodology considers a hybrid system composed by 518 PV panels, wind turbines, a diesel generator and lead-acid batteries as storage 519 solution. 520

The algorithm computes the optimal number of PV panels, wind turbines, 521 battery units and the energy provided by the diesel generator, constituting the 522 optimization variables of the problem, with the aim of minimizing the total Net 523 Present Cost (NPC) of the system over its entire lifetime. As input, a dataset based 524 on a measurement campaign performed in the month of June 2018 related to the 525 wind speed on site and the power consumption of the hut was used. These data 526 were collected each minute per each day and their hourly average values were 527 computed and used. The data related to the sun radiation were downloaded by 528 the PVGIS database. Two sizing approaches were evaluated: in one case, the 529 sizing of the components is based on the dataset of single days operation; alter-530 natively, the sizing is based on the whole dataset covering one month operation. 531

Based on these two approaches, the algorithm simulates the behavior of the op timal system over one month.

Results showed a strong variability related to the optimal sizing of power 534 generators and batteries in the HRES, which strongly depends on the variability 535 of the renewable sources as well as on the load profile. This demonstrates that 536 the proper selection and analysis of the dataset for sizing a HRES is fundamental 537 to obtain adequate performance. Considering only a daily load profile and a daily 538 pattern of both sun and wind sources, the HRES sizing could not meet the needs 539 of the load in all the days if a proper representative day of the entire month is not 540 defined. However, a lower capital cost would be required in most of the cases. On 541 the other hand, its sizing leads to an oversizing of the components when dealing 542 with the whole dataset. Therefore, a demand management could help to reduce 543 the size of the components and, at the same time, grate the energy supply when 544 the most demanding conditions occur. Results showed that: 1. the optimal siz-545 ing of a HRES strongly depends on the renewable sources and their variability, 546 2. the storage systems, coupled with conventional generators, are still necessary 547 to avoid the oversizing of the entire system, as well as of the batteries bank, 3. the 548 modulation of PV power, wind power and an eventual demand side management 549 strategy is crucial to avoid the oversizing due to the variable percentage of the 550 load to be satisfied each hour of the day, which decreases the difference between 551 the maximum and the minimum costs of the HRES . Results also demonstrate a 552 significant reduction of the GHGs emissions due to the use of renewable energy 553 technologies. Furthermore, a sensitivity analysis has been performed on both 554 the fuel and battery costs, showing how these parameters can influence the op-555 timal sizing of the system. In particular, considering a possible future scenario 556 characterized by a significant battery price reduction, HRESs would significantly 557 reduce their dependency on fossil-fuel conventional generators. 558

This algorithm constitutes a tool capable of providing a detailed description of different possible scenarios, thus helping engineers to design the system properly. Further developments of this investigation may include the use of a PHES equipped with Pumps-as-Turbines (PaTs) instead of conventional hydraulic turbines or conventional batteries storage systems. Indeed, the lower cost of PaTs compared to conventional hydraulic turbines and battery storage systems can reduce the total cost of an HRES, thus pushing further their future deployment.

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