Steady-State Operation of Islanded Distribution Network with PV and Wind Generation

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Abstract—**Energy management for islanded and small active distribution networks is more and more challenging due to intermittent distributed energy resource (DER) penetration increase. To this purpose, an optimisation-based framework in a co-simulation environment for the optimal steady-state operation of DERs integrated into small and islanded active distribution networks is proposed in this work. In particular, the optimal daily dispatch of DERs (i.e. wind turbine and photovoltaic), along with a battery energy storage system, is carried out to reduce biofuel consumption. The procedure is developed in Python and DIgSILENT PowerFactory for modelling and optimising system operation, while exploiting the quasi-dynamic simulation toolbox for better representing the network behaviour over daily time horizon. The approach is applied to a modified version of CIGRE Task Force C6.04 network and tested in three scenarios for evaluating the impacts of different DER level productions. The results showcase the potential for real-world application, and highlight significant improvements in DER management, contributing to enhance the operation of small active distribution networks.**

Keywords—Battery Energy Storage System, Co-simulation Framework, Distributed Energy Resource, Optimisation Problem, PowerFactory.

I. INTRODUCTION

The rapid evolution of power systems is driven by the transition towards a sustainable generation mix which requires a massive increase of distributed energy resources (DERs) such as photovoltaics (PVs), wind turbines (WTs). This transition necessitates advanced operation techniques to balance generation and demand along with battery energy storage systems (BESSs) [1], [2]. Different developed and developing islands are deploying WTs thanks to the average wind speed trends and availabilities and employ diesel generation as back-up [3]. However, small and islanded distribution networks face additional challenges in maintaining system stability, security, and balance while maximising DER production [4].

In literature the optimal dispatch, applied to distribution networks, is widely studied, with significant attention on the integration of DES and BESS. Previously, the research addressed the economic dispatch of fuel-based power plants, by minimising fuel costs [5], [6], greenhouses gas emissions [7], etc. Nowadays, with the integration of DERs, the focus is moved to optimising the operation of the generation mix (i.e. renewable and fuel-based sources) along with battery energy storage systems BESS [1], [5], [8]. Several works have employed specialised software such as HOMER [9] or DIgSILENT PowerFactory [3], others developed advanced optimisation algorithms, such as mixed-integer linear programming [10], [11], genetic algorithms [12], or particle swarm optimisation [13], for optimally sizing DERs, or hybrid BESSs in microgrids, or for demonstrating their operation to achieve a sustainable, efficient and feasible optimal management of intermittent.

Although DERs operation in large or micro grid-connected networks have been presented significant advancements, for small and islanded distribution networks there are currently significant study gaps in the literature regarding this topic [4]. For grid-connected systems the main existing research converges on solutions where services are provided by the main grid as well, putting the islanded network issues apart (e.g. system self-adequacy or -flexibility). On the other side, for microgrid networks there is an oversimplified model of the system in which reactive power balance or losses are neglected.

The potential of co-simulation techniques for combining full network models, through specialised software, with advanced optimisation or automatisation techniques, by programming languages, to assess the operation of these complex systems, continues to be largely unexploited [Vega, Diego Alejandro et al]. Among the different coupling between software and programming languages, the co-simulation framework between DIgSILENT PowerFactory and Python is widely spread, especially for exploiting AC load flow solutions in both operation and planning stages. A heuristic approach for expanding line capacities is proposed in [14], in which Python is exploited to automatise the load flow execution in different scenarios and to record the results of interest. Similarly, the authors of [15] use the Python-PowerFactory environment for automatising AC and load flow and hosting capacity toolboxes during time for sizing and siting BESS on transmission system level. The optimisation problem proposed in [16] is solved to define optimal BESS operation in a low voltage distribution network. In a second stage the solution is verified on PowerFactory through the quasi-dynamic simulation (QDS) toolbox. Regarding the optimisation-based methodologies, in [17] PV inverter reactive powers are optimised in a distribution system to minimise active power losses. A distribution system reconfiguration optimisation problem is carried out in [18], to minimise power losses and to reduce voltage deviations. In [19], the optimal capacity and location of BESSs and PVs are

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employed as variables to minimise distribution system active power losses.

The necessity of focused research on the optimization of DERs in small and isolated active distribution networks utilizing novel techniques that can handle their time-dependent constraints, like for BESS operation, is highlighted by this literature review. The aforementioned factors arise the necessity to establish novel solutions that improve the reliability and sustainability of these distribution networks. In this context, optimisation-based co-simulation framework provides the advantage of managing full network model in a direct and effective way in both planning and operation stages. This could contribute to reduce the actual gap, by adding the flexibility of programming environments and in power system specialised software capabilities.

In this paper a co-simulation approach to optimise DERs installed in small and islanded active distribution networks is proposed. In particular, taking the cue from [20], the procedure is conceived to minimise the daily biofuel consumption through the optimal dispatch of BESS and DERs while ensuring adequate voltage levels and preventing load curtailment in the presence of WTs as well. The co-simulation-based optimisation problem exploits the QDS toolbox of the software for directly embedding the full AC load flow equations as non-explicit constraints of the problem, providing a more detailed picture of network operation over time. This is a critical concern for guaranteeing the power supply to users in islanded grids. In particular, the optimisation problem is coded in Python language and the network modelling and analysis is performed through DIgSILENT PowerFactory. The framework practical relevance and potential for real-world implementation are showcased by its application to a modified version of the distribution network CIGRE Task Force C6.04. The main improvements introduced in this work, with respect to [20], could be summarised in:

- The inclusion of WTs to evaluate the benefits of different DERs in network operations along with the definition of proper active power production.
- The implementation and test of the methodology in different scenarios to evaluate the influence of high, average, and low DERs penetration in grid operation.
- The assessment of BESS power and energy exploitation, through dedicated indices, based on DERs production level.

In the following sections the paper is organised as follows. Sections II provides the co-simulation-based optimisation problem mathematical formulation. Section III presents the test system with focus on additional wind generation. Section IV briefly describes the co-simulation framework, whereas Section V discusses the obtained results. The last section remarks the key findings of the work.

II. PROPOSED METHODOLOGY

The proposed approach is based on a co-simulation paradigm to solve an integrated optimization problem in a distributed manner, which consists in the optimum management of DER in an islanded small active distribution network. It is established in a programming language environment by carrying out network steady-state analyses through a power system specialised software. This approach gives the possibility to use the numerical output resulting from the software solution as non-explicit objective functions or constraints in the optimisation problem.

In an islanded small active distribution grid, the sets of PVs Ω^P, WFs Ω^W, and loads Ω^L are individuated, along with a BESS and a biofuel generator, analysed during a daily time window Ω^T. In this context, the procedure controls BESS and DER active powers to minimise biofuel generator production while avoiding load curtailment.

The control action is established based on the solution of an optimisation problem formulated for maximising the objective function:

$$\max_{\boldsymbol{x}} f(\boldsymbol{x}) \tag{1}$$

where $\boldsymbol{x}$ is the state variable vector; it is composed of: $\boldsymbol{P}^P$ the vector of the PV active power setpoint $p \in \Omega^P$ at each time-step $t \in \Omega^T$; $\boldsymbol{P}^W$ the vector of WF active power $w \in \Omega^W$ and $t \in \Omega^T$, $\boldsymbol{P}^L$ the vector of load demand active power $l \in \Omega^L$ and $t \in \Omega^T$; $\boldsymbol{P^B}$ the vector of the BESS active power for each $t \in \Omega^T$. The objective function looks for maximising the active power outputs of PVs, WTs, and the BESS to supply load demands while minimising the biofuel generator production throughout the daily time window T:

$$f(\boldsymbol{x}) = \sum_{t\in\Omega^T}\left(\sum_{p\in\Omega^P} P^P_{p,t} + \sum_{w\in\Omega^W} P^W_{w,t} + \sum_{l\in\Omega^L} P^L_{l,t} + |P^B_t| - |P^F_t|\right) - f^s(\boldsymbol{x}) - f^v(\boldsymbol{x}) \tag{2}$$

where $\boldsymbol{P}^F$ is the biofuel active power vector of length T, whereas the network operating conditions are accounted by means of the penalty functions f^s and f^v. The former avoids the slack generator to provide negative active power values, and the latter avoids undesired voltage operating conditions, further details are provided in [20]. The state variables x of the objective function are subject to the following constraints. P^B_t is maximised taking into account its state of charge (SOC) updates and bounds, modelled as follows:

$$SOC_t = SOC_{t-1} - \frac{\tau}{e_r}\left(\frac{P^B_t}{P^{B_r}} + (1-\eta)\frac{|P^B_t|}{P^{B_r}}\right) \;\; \forall\, t \in \Omega^T \tag{3}$$

$$SOC_0 = SOC_T \tag{4}$$

$$SOC^{lb} \le SOC_t \le SOC^{ub} \;\; \forall\, t \in \Omega^T \tag{5}$$

$$-P^{B_r} \le P^B_t \le P^{B_r} \;\; \forall\, t \in \Omega^T \tag{6}$$

in which (3) updates the SOC at each time step depending on the previous SOC and the supplied or withdrawn power at time t; (4) binds the initial and final SOCs to be equal for reserving BESS energy for the next daily operation, whereas (5) and (6) bound the SOC and P^B_t within their lower (SOC^{lb}, $-P^{B_r}$) and upper (SOC^{ub}, P^{B_r}) bounds, respectively, at each time-step. In addition, τ is the time-step duration, expressed in fraction of hour, e_r is the energy ratio, P^{B_r} is the BESS nominal active power, and η is the BESS efficiency.

Furthermore, at each time-step, PVs, WFs, and loads are bounded to supply or withdraw active power between 0 and their maximum forecasted values ($P_{p,t}^{P,max}$, $P_{w,t}^{W,max}$, $P_{l,t}^{L,max}$):

$$0 \leq P_{p,t}^{P} \leq P_{p,t}^{P,max} \quad \forall\, t \in \Omega^T, \forall\, p \in \Omega^P \tag{7}$$

$$0 \leq P_{l,t}^{L} \leq P_{l,t}^{L,max} \quad \forall\, t \in \Omega^T, \forall\, d \in \Omega^D \tag{8}$$

$$0 \leq P_{w,t}^{W} \leq P_{w,t}^{W,max} \quad \forall\, t \in \Omega^T, \forall\, w \in \Omega^W \tag{9}$$

The proposed framework embeds full AC load flow equations as constraints of the problem during the analysed time window. Therefore, defining with Ω^N the set of the network nodes, the AC load flow equations can be formulated as follows $\forall\, t \in \Omega^T, \forall\, i \in \Omega^N$:

$$\begin{cases} P_{i,t} = \sum_{j \in i} Y_{ij} V_{i,t} V_{j,t} cos\left(\theta_{i,t} - \theta_{j,t} + \phi_{ij}\right) \\ Q_{i,t} = \sum_{j \in i} Y_{ij} V_{i,t} V_{j,t} sin\left(\theta_{i,t} - \theta_{j,t} + \phi_{ij}\right) \end{cases} \tag{10}$$

where $P_{i,t}$ and $Q_{i,t}$ are the net active and reactive power at bus i and time step t; $V_{i,t}$ and $\theta_{i,t}$ ($V_{j,t}$ and $\theta_{j,t}$) are the amplitude and phase of voltage at bus i (j) and time step t; Y_{ij} and ϕ_{ij} are the amplitude and phase of the nodal admittance between buses i and j.

Downstream the optimisation, the BESS exploitation is assessed through the following power (I_P) and energy (I_E) percentage indicators:

$$I_P = \frac{max(|\boldsymbol{P^B}|)}{P^{B_r}} \cdot 100 \tag{11}$$

$$I_E = \sum_{t=1}^{T^-} \frac{P_t^B \tau}{P^{B_r} e_r} \cdot \frac{100}{SOC^{ub} - SOC^{lb}} \tag{12}$$

where $|\boldsymbol{P^B}|$ is the vector of BESS absolute power values, T^- is the daily number of time steps the BESS is discharged.

III. TEST SYSTEM

The proposed approach is tested on a modified version of the CIGRE medium voltage distribution network, consisting of 15 buses distributed between two 20 kV feeders. Based on [20], the test system has been furtherly modified, including three WFs connected and sized based on the peak value of the connected nodal residential load, as in Fig. 1. Based on the Mauritius island tropical weather, characterised by low and constant wind speed values, as provided in the open-source weather data of [21],the WF is composed of 20 kW H-Darrieus wind turbines, whose features can be found in [22], for a resulting WF installed capacity of 0.8 MW. In addition, the 7.8 MW, 7/28 MW/MWh, and 3.4 MW of PV, BESS, and biofuel capacities, are considered. Operating constraints are taken into account for BESS, which has $SOC^{lb} = 0.15$, $SOC^{ub} = 0.85$, and $\eta = 0.95$. The system presents eight residential and six commercial loads, for a peak value of 5.235 MW. The studied system has daily horizon and hourly resolution ($\tau = 1$, $T = 24$).

In order to consider likewise system operating conditions, the methodology is performed in three different scenarios, based on different WF production, choosing days during 2023 with the highest, average and lowest wind speed values based on Port Louis co-ordinates [21]. Additionally, days have been chosen paying attention to the season and the day of the week to take the advantage of PowerFactory different daily trends for typical commercial and residential loads, along with PV system active power forecast, as provided in [23]. As a result, wind, PV and load profiles in simulated scenarios of maximum (S1), average (S2), and minimum (S3) WF production are depicted in Fig. 2, Fig. 3, and Fig. 4, respectively.

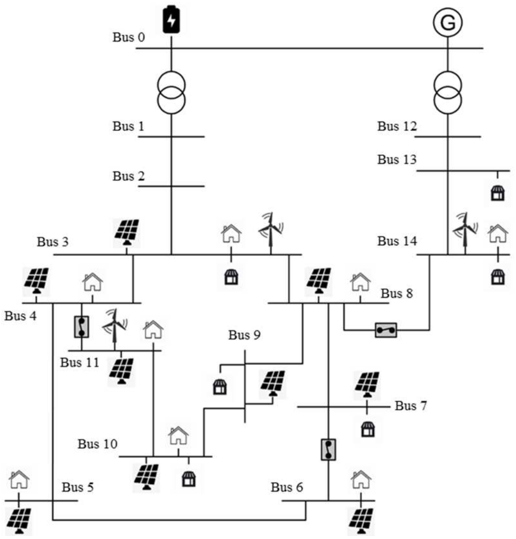

Fig. 1. Modified version of the CIGRE MV test system.

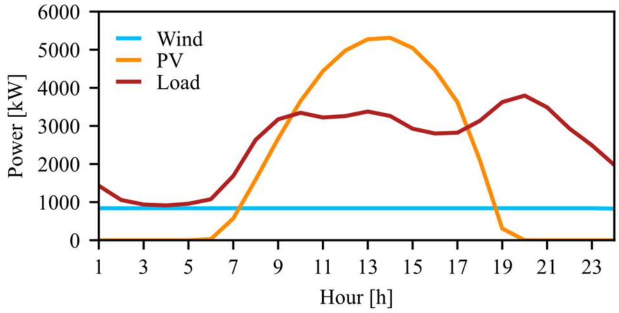

Fig. 2. Daily required load and PV and wind production in S1.

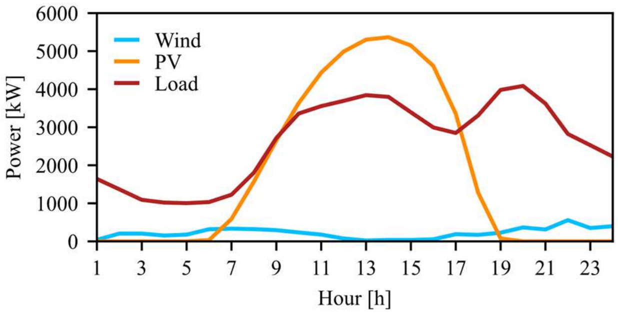

Fig. 3. Daily required load and PV and wind production in S2.

In S1 WFs produce the maximum power for the whole day resulting in 20.1 MWh, the PVs provide 44.0 MWh from h 6 to h 20 with a peak of 5.3 MW, whereas the load demand varies from 0.9 MW to 3.8 MW and the daily required energy is 60.3 MWh. In S2 the daily required load is 63.0 MWh and it ranges from 1.0 MW up to 3.8 MW, the PVs produce 43.0 MWh with a 5.4 MW peak value, whereas the WFs produce 5.3 MWh with a variation between 23 kW and 558 kW. Finally, in S3 the WFs production is null for nine hours and they supply 1.3 MWh in the rest of the day, the PVs provides 27.9 MWh from h 6 to h 19 with a peak production of roughly 4.0 MW, and the required load is 61.9 MWh with a maximum amount of 3.6 MW.

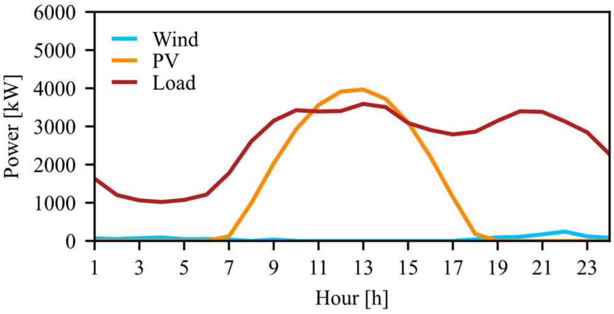

Fig. 4. Daily required load and PV and wind production in S3.

IV. CO-SIMULATION FRAMEWORK

The co-simulation-based framework exploits the QDS toolbox of PowerFactory for modelling the equations (10) as implicit constraints of the optimisation problem (1)–(9) which is developed in Python through the SciPy library [24] and solved with the SLSQP (Sequential Least Squares Programming) method contained in the same library. Detailed information and the key advantages of this co-simulation framework between Python and PowerFactory are provided in [25]. The problem is performed on a computer with 32 GB RAM, 12th Gen Intel® Core™ i7-12700F CPU @ 3.60 GHz, 12 physical cores and 20 logical processors. The optimisation problem is averagely solved within 3 minutes and 9 seconds for the three scenarios.

The load flow simulations are performed setting the biofuel as slack generator, and it is the only element enabled to control the nodal voltages. The penalty function f^v and f^s are set in order to obtain a penalty value of one order greater than the other terms of (1). For the three scenarios the BESS initial SOC is 0.5 and the active power bounds are the maximum charge and discharge power, i.e. P^{B_r} and $-P^{B_r}$, respectively. The optimisation problem initial condition of the state variables is set as follows. For the PVs ($P^P_{p,t}$), loads ($P^L_{l,t}$), and WF ($P^W_{w,t}$) the hourly active power are set as the maximum hourly estimation of S1 (Fig. 2), S2 (Fig. 3), and S3 (Fig. 4). For the BESS, the active power initial guess, for each time step, is:

$$P^B_t = \sum_{l\in\Omega^L} P^{L,max}_{l,t} - \sum_{p\in\Omega^P} P^{P,max}_{p,t} - \sum_{w\in\Omega^W} P^{W,max}_{w,t} \qquad (13)$$

hence, the hourly difference between the total required load and the DER production. Finally, the SOC initial guess is obtained according to (3) with the initial guess of P^B_t at each hour, paying attention to not exceed the upper and lower bounds.

V. RESULT DISCUSSION

The optimal values resulting from S1 are depicted in Fig. 5 and Fig. 6. In particular, Fig. 5 shows the daily active power schedules of the system DERs. As observed, the WTs production is not curtailed and equals the values depicted in Fig. 2, whereas the PVs are curtailed and their daily production is reduced by roughly 14.8% (i.e. 6.5 MWh) in the middle hours of the day (i.e. when DER production is greater than the required load). This is due to the low exploitation of BESS in the first hours of the day for the low required load and, followed by a significant PV generation surplus that results in the accomplishment of the BESS SOC upper bound at hour 17, as observable in Fig. 6. At the ending hours of the day, the BESS is partially discharged in order to equal the final SOC to 0.5, as per (4). As a result, the total energy supplied and withdrawn by BESS is 11.2 MWh and 12.4 MWh, respectively, and the difference is imputable to round trip efficiency. The biofuel, being the slack generator, provides 4.3 MWh and is mainly employed at the end of the day, when the BESS cannot be totally discharged. In S1 the daily energy losses are roughly 0.47 MWh, i.e. 0.78% of the load demand. PV productions have been curtailed in the optimal daily schedules of this scenario rather than WTs, in order to comply with BESS energy constraint. This could be ascribable to the greater spread of PV generators into the grid (see Fig. 1), therefore their curtailment could yield lower losses. For purpose of verification, the optimisation problem has been re-executed by setting the PV production as a known input. As a consequence, the wind is curtailed during the same hours by the same quantity, but with roughly 4% increased losses covered by the biofuel generator, i.e. the solution is suboptimal with respect to the PV curtailment.

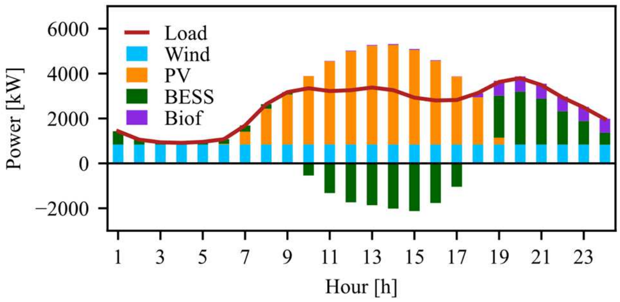

Fig. 5. Optimal daily active power schedules in S1.

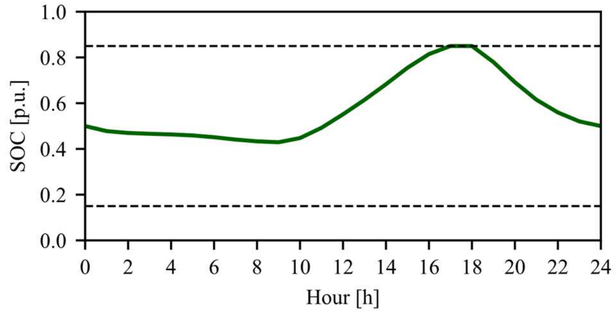

Fig. 6. BESS optimal state of charge in S1.

The optimal schedules obtained in S2 are depicted in Fig. 7, along with the resulting BESS SOC reported in Fig. 8. In this case both WTs and PVs are not curtailed and their production equal the trends depicted in Fig. 3. In the middle hours of the day BESS charges 14.3 MWh by PVs generation surplus, reaching the SOC upper bound at hour 17 (Fig. 8), whereas, in the rest of the day, it delivers 12.9 MWh. In this scenario the biofuel production is 16.7 MWh and it is mainly supplied, as in the previous case, after the dusk (9.2 MWh). In this scenario, the system energy losses are approximately 0.69 MWh, i.e. 1.1% of the required load.

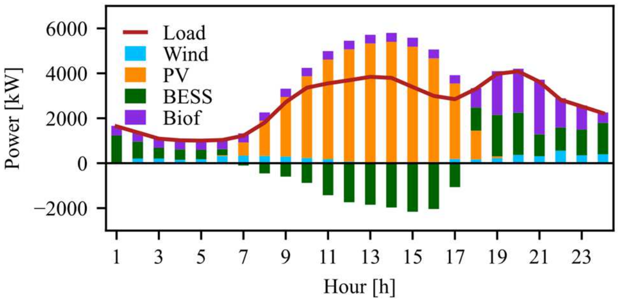

Fig. 7. Optimal daily active power schedules in S2.

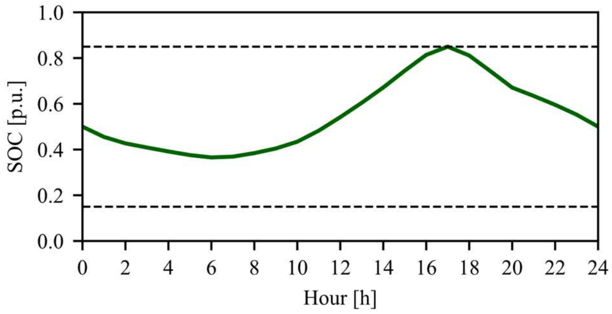

Fig. 8. BESS optimal state of charge in S2.

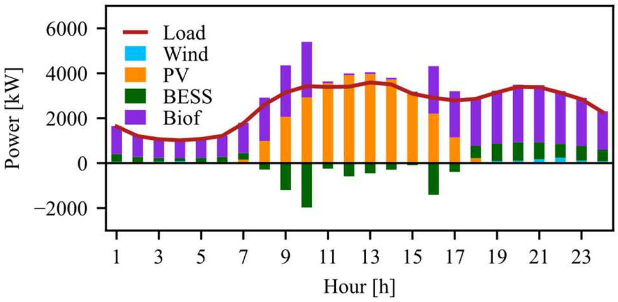

Fig. 9. Optimal daily active power schedules in S3.r

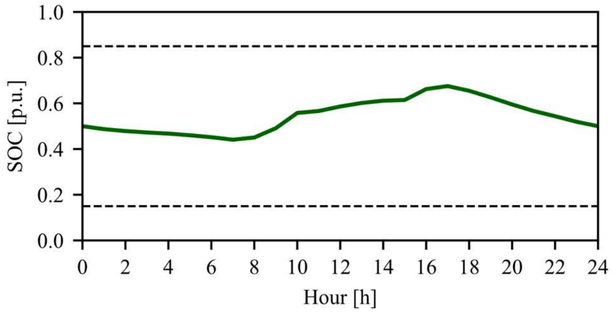

Fig. 10. BESS optimal state of charge in S3.

Finally, the optimal values obtained in S3 are depicted in Fig. 9, whereas the resulting daily BESS SOC is depicted in Fig. 10. Due to the low production, PVs and WTs are not curtailed, suppling 27.9 MWh and 1.3 MWh, respectively, as depicted in Fig. 4. As consequence, the BESS is lowly exploited, delivering only 6.3 MWh in the early morning and late evening, and getting 6.9 MWh back in the middle hours by a mix of PVs and biofuel production since only from hour 11 to hour 15 the PV production is greater than the required load. The resulting biofuel daily production is 34.0 MWh (i.e. half of the required load) and it is mainly exploited in the late evening and the middle hours for charging the BESS. The daily system losses observed in this scenario are roughly .65 MWh, representing the 1.1% of the required load.

In TABLE I. the BESS power and energy exploitation indices obtained in the three scenarios are showcased. The high DER penetration of S1 provides an exploitation of BESS power greater than 33%. However, the small discharge in the beginning of the day, due to high wind production and low required load, does not allow to fully exploit its energy range, which is roughly 57%, and causes the PV curtailment since the BESS reaches the full charge. In contrast, in S2 the BESS energy range is better exploited, greater than 65%, although the DER production is lower than in S1. This is caused by the higher coverage of the load demand in the early morning which allows to fully charge the BESS without curtailing DERs. In the last scenario, the low DER penetration does not allow to exploit the BESS in both power (28.2%) and energy (31.9%) ranges. The obtained BESS exploitation is ascribable to the initial SOC value along with the constraint (4), In fact, in S1 the initial SOC could be lowered in order to better utilise the highly DER production which could be stored rather than curtailed. On the contrary in S3 the biofuel output could be reduced in the first hours of the day by increasing the initial SOC. In addition, a suitable forecast of the DERs, along with load demand, of the next day could be helpful for choosing the SOC at the end of the day in (4).

TABLE I. BESS EXPLOITATION INDICIES.

Scenario	Power Range Exploitation [%]	Energy Range Exploitation [%]
S1	33.6	57.3
S2	30.9	65.8
S3	28.2	31.9

VI. CONCLUSIONS

In this work, a co-simulation procedure for optimally managing DERs in a small and isolated active distribution network has been proposed. The goal is to minimise biofuel production by optimally exploiting WTs and PVs production and BESS power exchange for supplying the daily load demand. The approach is developed in DIgSILENT PowerFactory-Python environment to take the advantages of detailed power system models and of optimisation flexibility, respectively, and the relevant computational time has been consistent with the daily schedule period for generation and consumption.

The co-simulation findings have shown that DERs daily active power production has been influenced both by minimisation of the objective function and by network constraints. In fact, during high DER availability days, the biofuel power production could be lowered down to 10% of the required load. Nonetheless, the high DER production could be subjected to a curtailment, due to BESS management over the day, depending on generation location and distribution affecting network losses. On the contrary, on days with weak DER production, biofuel has a pivotal role for ensuring load demand supply, up to 50%, while supporting cyclical BESS operation as well.

The optimal management of BESS operation can be enhanced by properly choosing its initial and final SOC, not necessarily at the same value. However, this would require reliable mid-term DER and load forecasts, to avoid BESS shortage for the next day. Further improvements could address cost optimisation and reserve deployment, thanks to the flexibility of the approach for possible extension to inter-hour time-step operation (i.e. half- or quarter-hour), in order to be compliant with new European electricity market rules.

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