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Increasing the Photovoltaic Hosting Capacity in Autonomous Grids and Microgrids via Enhanced Priority-List Schemes and Storage

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Abstract

European Union has seen a rapid increase in renewable energy sources during the last decade. The variability and uncertainty caused by the increased penetrations of renewable generation must be properly considered in day-ahead unit commitment to retain the stable operation of conventional power plants. In this work, we present an enhanced method to determine the hosting capacity of photovoltaic energy in an autonomous grid. Based on optimal unit commitment schedules derived from priority list-schemes, we examine the potential of increasing the hosting capacity performing annual simulations for different scenarios in the presence of electricity storage. According to the obtained results, the application of storage eliminates the reliability expenses of load shedding and spinning reserve deficits. Hence, the actual hosting capacity is appropriately retrieved based on the renewable generation curtailment during each case study. However, sustainable solutions are achieved at higher penetration levels, reaching a near of 20% with respect to photovoltaic systems. The proposed solution could be efficiently utilized to determine the photovoltaic hosting capacity of microgrids in islanded or interconnected mode.

Keywords: Photovoltaic energy; hosting capacity; autonomous grids; microgrids; priority list-schemes; electricity storage

1. Introduction

Electrical energy is crucial for the development, progress, and overall lifestyle in the global economy. In contrast to other ordinary commodities, electricity is produced the instant it is consumed. This forms a serious challenge for generating systems since the demand exhibits significant variations throughout a day with amplitudes that are way greater than the maximum capacity of any individual generating unit [1]. On the other hand, the power generation sector has seen a rapid growth globally due to the increasing industrialization, transportation demand and domestic appliances. Historically earlier, the proper adjustment of production to consumption could be realized by making use of dispatchable and controllable conventional power plants. In general, thermal generating units could appropriately satisfy the requirements of pretty predictable and tractable load profile exploiting fossil fuels, while the transmission and distribution of electrical energy was performed via passive power networks based on simple control logics [2,3].

Current efforts aiming to shift towards de-carbonization give rise to remarkable challenges for power systems and their operators [4]. The depletion of fossil-fuel reserves, global warming and associated extreme weather conditions have motivated European Union (EU) to expand the share of intermittent renewable energy sources (RES) for electricity production. This eventually transformed power grids into active complex systems with bidirectional flows that increase the uncertainty at both generation, transmission, and distribution sections. To gradually reach the EU targets with respect to the RES share in their energy mixture, the EU member-states devise strategies towards the electrification of transport and heating/cooling sectors which are responsible for a radical reshaping of daily load demand profiles. This way, the intelligent scheduling of power systems for the seamless integration of intermittent RES, plug-in electric vehicles (PHVs) and weather-dependent devices constitutes a crucial solution in delivering future low carbon energy [5,6].

The variability and uncertainty caused by the increased penetrations of RES must be properly considered in day-ahead unit commitment (UC), optimal power flow (OPF) and even real-time economic dispatch (ED) problems. Consequently, besides achieving minimum generation cost, modern generation schedules must satisfy a larger set of different complex constraints. These account for the generation constraints in the presence of renewable generation, network constraints affected by the distributed energy resources, bilateral contracts enclosing independent electricity provision, reliability and stability power auctions, net-metering and feed-in-tariff prosumers, corrective security actions in sudden load variations or outage circumstances, and so on [7]. It is obvious that the development of active power networks due to the intermittency of renewable energy and the randomness of the incentivised load at the demand side, leads to growing concerns in relation with the added operating uncertainty.

In contrast to conventional systems that can be carefully timed to be dispatched and contribute to generation, renewable sources are strictly correlated to imperfectly predictable and uncontrollable weather conditions. In this regard, unit commitment becomes one of the highest priority optimization problem by which the adequacy of a power system can be evaluated and planned-ahead to offer a large profitable return [8]. The added volatility in net load caused by the increasing penetration of renewable generation have motivated the study of alternative approaches that account for the necessary flexibility, without affecting the stable operation of conventional power plants. However, the simultaneous increase in electricity demand and reduction of conventional sources contribution create a lot of power integration issues which undeniably disturb the overall system reliability [9]. Turning to the specification of the amount of new production or consumption that can be connected to the grid without endangering the power quality for other customers, many research works aim at quantifying the hosting capacity (HC) in modern power systems [10]. Although the concept was assessed exclusively for distribution networks [11–14], it constitutes a specific, measurable and practical term to investigate and analyse the overall system performance by making use of various indicators.

Many representative research works have focused on the impact of enhanced RES integration without concentrating on their maximum permissible rate. Specifically, in [15] a wind-hydro pumped storage plant is introduced as a practical paradigm for high-RES penetration in autonomous island systems. Taking into account the intra-hourly net demand variability, the optimal generation scheduling of a hybrid diesel/wind/pumped-storage isolated system is presented in [16]. In order to determine the number of over-frequency events, the authors in [17] analysed the impact of wave energy generation on the power system frequency for the particular case study of Tenerife Island in Spain. To minimize these excessive deviations, several techniques and control strategies involving variable speed wind turbines (VSWTs) have also been investigated in isolated power networks [18]. Similar control strategies were also proposed in [19] for inertial contribution to frequency regulation and the use of Pelton turbines as synchronous condensers. Both strategies do not involve a significant loss in the efficiency or in the availability of wind energy. In [20], the contribution of non-conventional pumped-storage configurations such as variable-speed pumping and hydraulic short-circuit, have been examined in an attempt to reduce the scheduling cost and wind curtailment of an isolated power system considering the impact on CO_2 emissions. With the aid of virtual power plants, two further studies involved the presence of centrally managed battery energy storage (BES) facilities with diversified system characteristics under high-RES penetration conditions [21,22]. Finally, it is worth noting that the most common methods conducted to solve UC in indicative non-interconnected island power systems are the Benders decomposition technique [16], priority list schemes [23] and mixed-integer linear programming approach [24].

In this work, we present a different approach to increase the photovoltaic hosting capacity in autonomous systems. We provide a comprehensive formulation of the UC objective including different electricity storage (ES) parameters. Following a thorough analysis with respect to the imposed system-wide and unit-specific constraints, we propose a solution based on enhanced priority-list schemes. The simulation studies as well as their experimental evaluations rely on actual data and real-world scenarios for a representative power system between EU and Asia, which can be viewed as a microgrid with interconnection capability to large-scale networks. The rest of the paper is organised as follows. The following section deals with the problem formulation and the proposed method for solution. In Section 3, a descriptive presentation relating to the considered power system is carried out. The experimental simulations are also included along with a comparative discussion of the obtained results. Finally, the conclusions are drawn in Section 4.

2. Problem Formulation and Methodology

Unit commitment constitutes a very well-known task in electricity industries and provides the ability to save a lot of money on an annual basis by making use of exact mathematical and/or (meta)heuristic mechanisms. Although it possesses a non-convex, multi-variate, mixed-integer and extremely non-linear objective, optimal UC schedules can lower the total production cost in terms of fuel avoidance costs and other expenses [25,26].

2.1 Unit commitment problem formulation

To obtain an optimal scheme that meets the power demand at a minimum operating cost by optimizing the binary on/off status of power generation units, UC considers economic dispatch as a sub-problem for the evaluation of the real valued power output of the corresponding units [27]. In this regard, the generic objective function takes into account the operational costs together with some penalty expenses, which are formulated as follows:

$$f = \min_{P_i^t, U_i^t} \left\{ \sum_{t=1}^{T} \left[\sum_{i=1}^{N} C_i^t \left(P_i^t, U_i^t \right) \right] + C_{RES}^t + C_{ENS}^t + C_{RNS}^t \right\} \quad (1)$$

The total production cost f is defined by the total operational cost C_i, the RES curtailment cost C_{RES}, the penalty cost for the energy not served C_{ENS} and reserves not served C_{RNS}, which are expressed via equations (2) – (5), respectively.

$$C_i(P_i^t, U_i^t) = \left[a_i.(P_i^t)^2 + b_i.P_i^t + c_i + (1 - U_i^{t-1})SU_i\right]U_i^t \quad (2)$$

$$C_{RES}^t = E_{RES}^t.c_{res} \quad (3)$$

$$C_{ENS}^t = c_{ens}\left\{P_{NL}^t - \sum_{i=1}^{N} P_i^t\right\} \quad (4)$$

$$C_{RNS}^t = c_{rns}\left\{SR^t - \left[\sum_{i=1}^{N} P_{i,max-cap}^t - P_{NL}^t\right]\right\} \quad (5)$$

Denoting the binary on/off status with U, each generating unit i can supply the real power output P during interval t. a, b and c are the fuel-cost coefficients of each generator, while SU expresses their individual start-up cost. The curtailed RES energy is computed as $E_{RES} = P_{RES}.t$. The energy not-served (also known as load shedding) refers to the subtraction of net-load demand (P_{NL}) and summed production of the committed units during t, whereas the reserves not-served accounts for the deviations between the required spinning reserves (SR) and available capacity.

The overall scheduling is subjected to a large set of different constraints which, in general, are separated into three main categories. The first category concerns the coupling constraints of power balance (equality constraint) and spinning reserve (inequality constraint) and are presented in the respective equations (6) and (7).

$$\sum_{i=1}^{N} P_i^t - P_{dis}^t = P_{NL}^t + P_{ch}^t \quad (6)$$

$$\sum_{i=1}^{N} P_{i,\max\_cap}^t \geq P_{NL}^t + SR^t - (P_s^t + P_{ch}^t) \quad (7)$$

To avoid load shedding, the actual demand must be satisfied throughout the time-horizon T. The power output from RES is typically treated as negative load, possessing the priority in electricity mixture. In the presence of electricity storage, the charging (P_{ch}) and discharging (P_{dis}) power are included in the balance equation [28]. Regarding the required spinning reserves, their total amount is favoured by the energy stored (P_s) and charging process. SR takes into account the deviations that can occur due to forecast errors associated with RES generation, load demand and unintentional equipment failures. Hence, its composition relies on different factors to independently include the firm, variable or uncertain RES, the price-responsive, weather-sensitive or multi-sector electrification load demand (P_L), and other reliability parameters associated with the electric power network such as *N-1* criterion. These factors are denoted by ξ and a commonly used example is demonstrated in equation (8).

$$SR^t = \xi_1 P_{firm}^t + \xi_2 P_{var}^t + \xi_3 P_{unc}^t + \max\{\xi_4 P_L^t, \max[U_i^t P_{i,max}^t]\} \quad (8)$$

To make our formulation more realistic, we also include two important storage parameters, namely efficiency (n) and self-discharge rate (SDR). The relationship between the charged (E_{ch}), stored (E_s) and discharged (E_{dis}) energy can be obtained with the aid of equations (9) – (11).

$$E_s^t = n_{ch} E_{ch}^t \quad (9)$$

$$E_s^{t+t_s} = E_s^t . (1 - SDR)^{t_s} \quad (10)$$

$$E_{dis}^{t+t_s} = n_{dis} E_s^{t+t_s} \quad (11)$$

The charged energy is reduced due to the imposed charging losses based on charging efficiency n_{ch}. At the end of the charging process, the energy stored is degraded according to SDR and storage duration t_s. The final discharging energy decreases based on the discharging efficiency n_{dis}. During the storage duration, part or total of the stored energy can be withdrawn to respond to a sudden power balance violation. The absolute amount in terms of power is computed via the following expression:

$$P_s^t = \min\{E_s^t . n_{dis}, P_{rated}\} \quad (12)$$

where P_{rated} denotes the rated power of the storage medium.

The second category accommodates the unit-specific (inequality) constraints (13) – (19) that the optimization process must satisfy. The boundaries refer to the minimum (P_{min}) and maximum (P_{max}) capacity that force each generator to operate within the permissible range. Following are the consecutive constraints that restrict the status and the power output of each unit according to their previous state. These account for the minimum required time (*MU* and *MD*) that must be elapsed before a generator can change its status and the maximum upward (*RU*) and downward (*RD*) ramping capability. The status restriction is a further constraint that allows a generator to run in three possible states, namely in must-run, must-out and fixed-MW output mode. The last constraint of this category relates the initialization of the process with the actual conditions (*I.C.*) of the available *N* generating units during previous schedules. These may include the on/off status of each generator unit, the real-valued power output and the time duration from the last start-up and shut-down.

$$P_{i,\min}^{t}.U_i^t \leq P_i^t \leq P_{i,\max}^{t}.U_i^t \quad (13)$$

$$U_i^t = 1 \rightarrow 0 \quad if \quad \sum_{t=tu}^{t-1} U_i^t \geq MU_i \quad (14)$$

$$U_i^t = 0 \rightarrow 1 \quad if \quad \sum_{t=td}^{t-1} (1 - U_i^t) \geq MD_i \quad (15)$$

$$P_i^t - P_i^{t-1} \leq RU_i, \quad if\ P_i^t > P_i^{t-1} \quad (16)$$

$$P_i^{t-1} - P_i^t \leq RD_i, \quad if\ P_i^t < P_i^{t-1} \quad (17)$$

$$\forall t \in \mathcal{T} \begin{cases} U_j^t = 1 & , if\ j^{th}\ unit\ must\ run \\ U_j^t = 0 & , if\ j^{th}\ unit\ must\ out \\ P_j^t = \begin{cases} 0 & if\ U_j^t = 0 \\ P_{j,fixed} & if\ U_j^t = 1 \end{cases} & , if\ j^{th}\ at\ fixed \end{cases} \quad (18)$$

$$I.C. = \begin{cases} +min\left\{MU_i, \sum_{t=tu}^{T} U_i^t\right\} \\ -min\left\{MD_i, \sum_{t=td}^{T} \left(1 - U_i^t\right)\right\} \end{cases} \quad (19)$$

t_u and t_d are the actual times of the last start-up and shut down, respectively.

The final constraint falls in the third category and is treated as a plant-wide limitation. This kind of constraint restricts the number of generating units that can simultaneously start-up or shut down. This number is directly proportional to the number of available power plant operators (crew size). The plant crew constraint (*Cr*) is expressed as follows:

$$\sum_{i=1}^{N} U_i^t \left(1 - U_i^{t-1}\right) + U_i^{t-1}\left(1 - U_i^t\right) \leq Cr^t \quad , \forall t \in T \quad (20)$$

2.2 Enhanced priority-list schemes formulation

Within the wide variety of methods, priority list schemes present a simple, exact approach without requiring extra parameters tuning or extreme knowledge about each independent system to extract an optimal solution. In addition, it occurs advantageous in convergence times in contrast to heuristic and meta-heuristic alternatives which must deal with the burden of exploration/exploitation trade-offs [29]. Compared to mathematical techniques which commonly rely on dual optimization, the priority-list approach does not suffer from the identical heat-rate sensitivity; this forms a great advantage in autonomous systems which consist of several identical generating units in terms of heat-rate coefficients and start-up costs [4].

Since the contribution from RES constitutes the priority in electrical energy generation, priority list schemes can be utilized to commit conventional generators until the residual load demand is satisfied. Instead of extracting the order based on conventional priority-based approaches which rely on single-factor reordering, we propose an enhanced priority list that can be obtained based on the following model. Apart from the incremental cost of each independent generator, the model takes into account also the maximum capacity, the minimum up time and start-up cost. Equations (21) – (24) are utilized to define the considered four factors, while the optimal priority is given based on the normalization function of equation (25).

$$F_i^{(1)} = \left.\frac{d\big(F(P_i)\big)}{dP_i}\right|_{\substack{i \neq j \\ P_i = \frac{P_{i,min}+P_{i,max}}{2}}} \quad (21)$$

$$F_i^{(2)} = P_{i,max} \quad (22)$$

$$F_i^{(3)} = MU_i \quad (23)$$

$$F_i^{(4)} = SU_i \quad (24)$$

Our enhanced approach introduces the fundamental assumption that the new configuration is determined with the ascending order of the developed list, considering the available units (or excluding the must-run units *j*) and relying on equation 25.

$$F_i^* = \frac{F_i^{(1)}}{min\left(F_i^{(1)}\right)} + \frac{1}{\left(\frac{F_i^{(2)}}{min\left(F_i^{(2)}\right)}\right)} + \frac{1}{\left(\frac{F_i^{(3)}}{min\left(F_i^{(3)}\right)}\right)} + \frac{1}{\left(\frac{F_i^{(4)}}{min\left(F_i^{(4)}\right)}\right)} \quad (25)$$

3. Test System and Experimental Results

In this section we present the considered power system composed by 20 thermal generating units and domestic renewable technologies including photovoltaic parks, wind farms and biomass plants. This is the autonomous system of the island of Cyprus, which forms a representative isolated power network within EU with the opportunity of being viewed as a microgrid formation for the hyper-grid of both European and Asian continents. Following a brief analysis with respect to the load profile and RES contribution, we investigate the increase in PV penetration from the hosting capacity perspective. The PV contribution is represented by different penetration scenarios and the hosting capacity is obtained by minimizing the penalty parameters in the objective function (1), namely the RES curtailment, load shedding and spinning reserve deficits.

3.1 Descriptive presentation of the island system

All characteristics pertaining the thermal generating units are listed in Table 1. The total annual generation for the year of 2020s was 4,807.11GWh. Thermal units and RES technologies contributed with 4,246.106GWh and 561GWh, respectively. Based on the estimated station and network losses, the share of RES injected into the grid was rated at 11.7%. It is noted that 227.7GWh consumed for the local needs of thermal power plants, while the transmission and distribution losses accounted for 1.35% and 2.8%, respectively. By the end of the same year, the installed capacity of the distributed energy resources (DER) reached 243.6MW, with 12.1MW coming from biomass units, 229.1MW from photovoltaic systems and 2.4MW wind turbines. A total of 54MWe is provided by net-metering scheme which is addressed to all consumers that possess a small installed PV system with capacity no greater than 10kWe. Finally, the rest of 155.1MW wind power is accommodated by the transmission power network [30].

Table 1 Operational features of the thermal generating units.

Unit	P_{min}	P_{max}	a	b	c	SU	RU/RD	MU	MD
1	4	37	0.107	33.92	474.5	104	75	1	0.5
2	4	37	0.107	33.92	474.5	104	75	1	0.5
3	4	37	0.107	33.92	474.5	104	75	1	0.5
4	4	37	0.107	33.92	474.5	104	75	1	0.5
5*	30	58	0.141	31.07	501.4	5786	30	2	8
6	30	58	0.141	31.07	501.4	5786	30	2	8
7	30	58	0.141	31.07	501.4	5786	30	2	8
8	30	58	0.141	31.07	501.4	5786	30	2	8
9	30	58	0.141	31.07	501.4	5786	30	2	8
10	30	58	0.141	31.07	501.4	5786	30	2	8
11	8.75	17	0.011	31.12	77.4	66	15	1	2
12	8.75	17	0.011	31.12	77.4	66	15	1	2
13	8.75	17	0.011	31.12	77.4	66	15	1	2
14	14.5	17	0.219	25.83	93.8	66	15	1	2
15	14.5	17	0.219	25.83	93.8	66	15	1	2
16	14.5	17	0.219	25.83	93.8	66	15	1	2
17*	66	124	0.033	28.35	618	9200	63	12	8
18	66	124	0.033	28.35	618	9200	63	12	8
19	66	216	0.02	21.6	1238.4	208	180	8	6
20	66	216	0.02	21.6	1238.4	208	180	8	6

* The specific generating units operate constantly in must-run mode.

The load factor of conventional power plants shows a decreasing annual trend in relation to the annual peak demand depicted in Figure 1. The maximum RES output by category is presented in Figure 2.

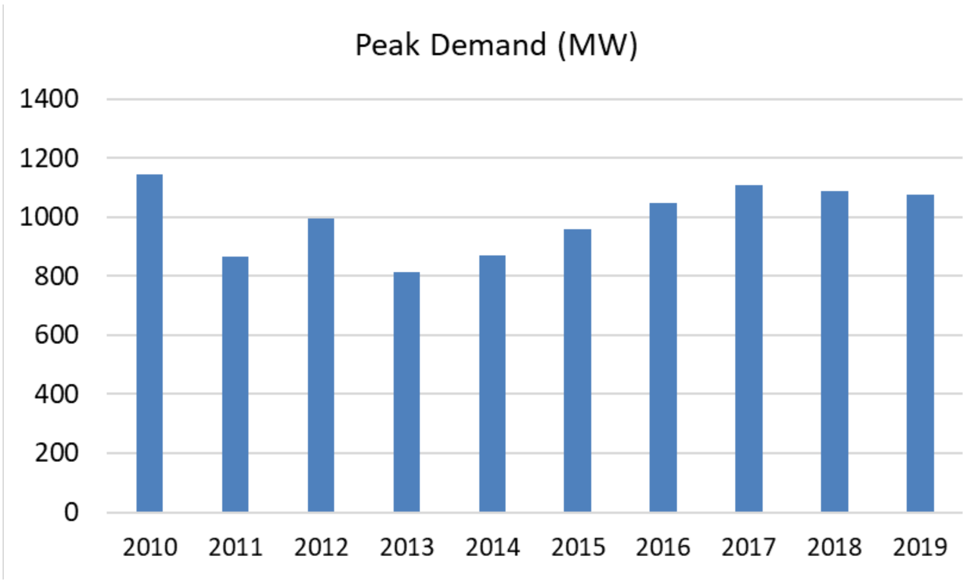


Figure 1 Annual peak load demand.

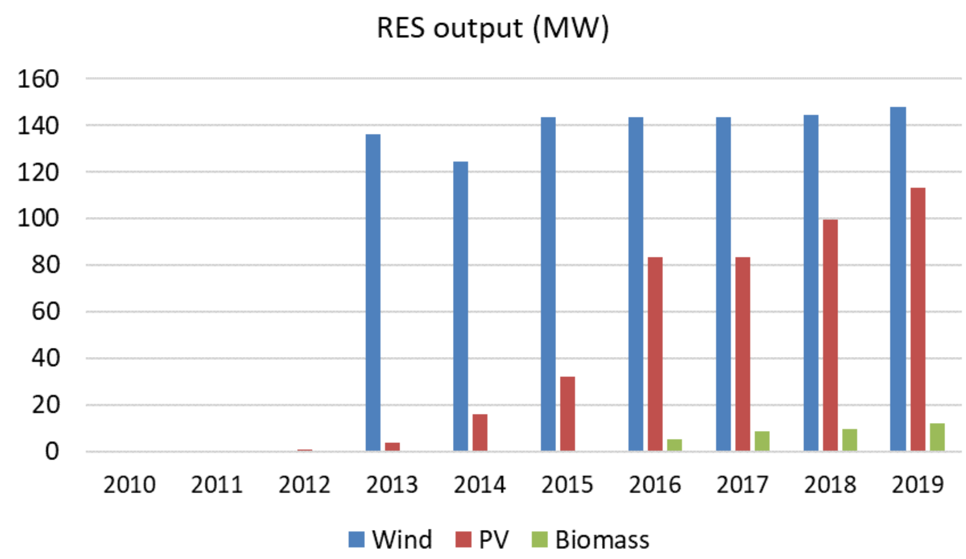


Figure 2 Renewable maximum power output per year.

As can be observed, the RES installation trend seems to favor PV systems due to their relatively predictable power output which approximately follows the daily human activity. In addition, despite the tremendous increase in domestic appliances during the 2010's decade, the governmental incentives towards the enhancement of energy efficiency and residential consumption mitigation via net-metering programs led to steady low and respectively constant peak loads. To offer a more detailed explanation regarding the actual contribution of RES, we illustrate the fluctuation of actual load demand in Figure 3 and the corresponding renewable penetration in Figure 4 during the year of 2020. We consciously select January, April, July and October as the second and most representative months per season.

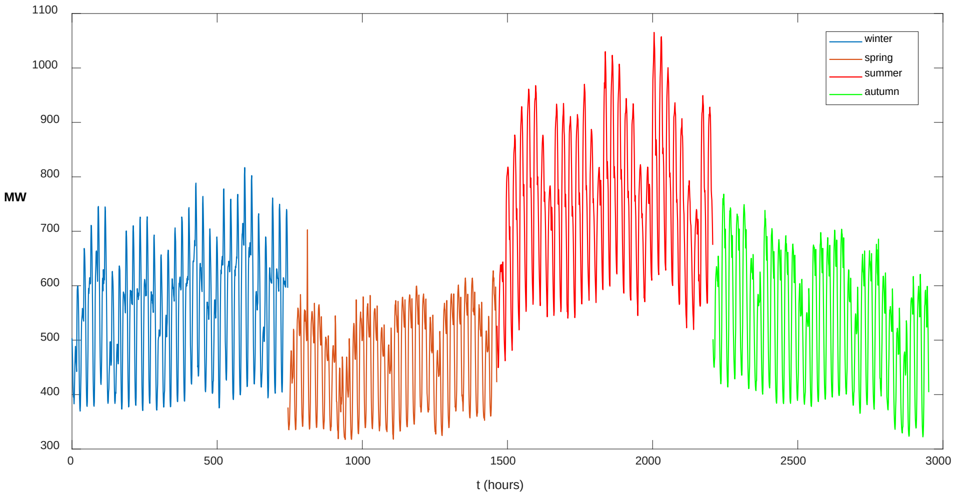
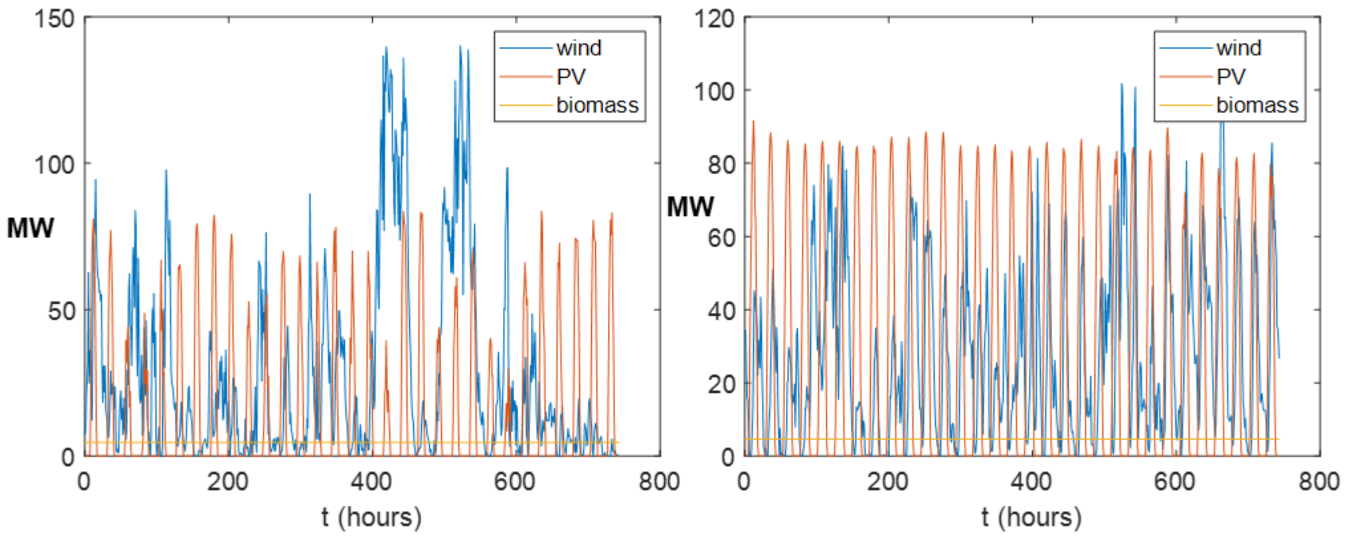


Figure 3 Hourly fluctuation of seasonal load demand.



(a) *(b)*

Figure 4 RES contribution pertaining a *(a)* winter and *(b)* summer month.

While biomass constitutes a firm input, PV and wind concern volatile renewable imports and thus the SR formulation must differ accordingly. To appropriately choose a realistic factor ξ for each case, the daily formulation of wind farms was taken into account (Figure 5).

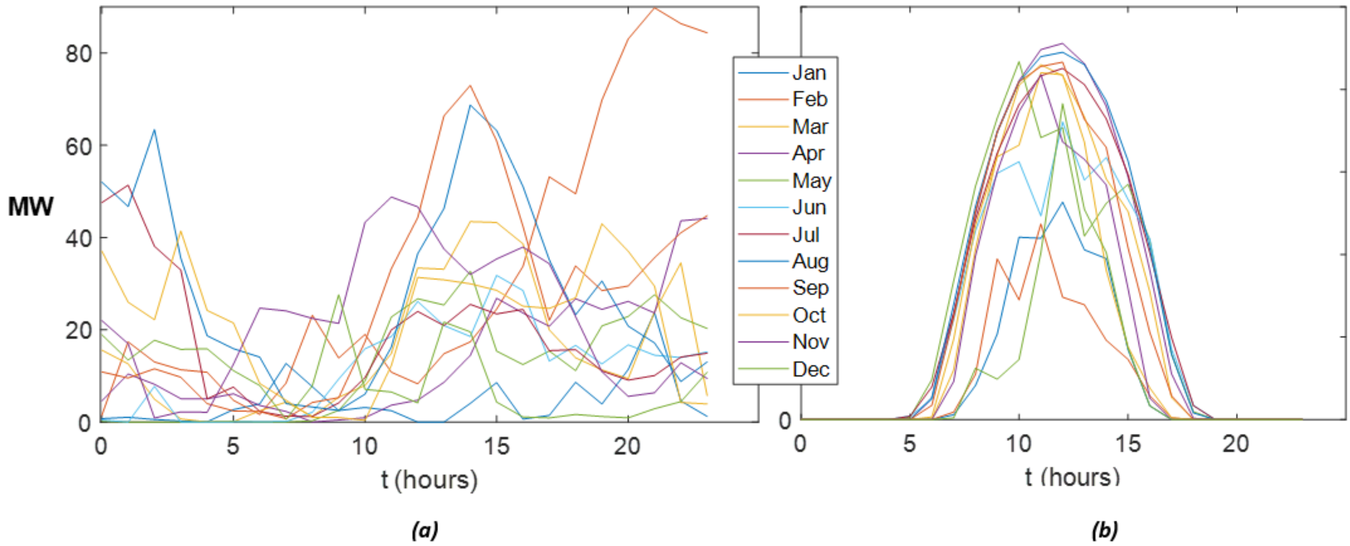


Figure 5 Daily fluctuation of *(a)* wind and *(b)* PV output per month.

Consequently, PV generation is considered as variable source of energy in contrast to wind that forms an inherently uncertain power input. In the following section, an attempt is undertaken to examine the PV hosting capacity in the presence of electricity storage. The experimental evaluation relies on the actual load demand of 2020 along with the RES contribution per category. For this purpose, the seasonal range of PV power is depicted in Figure 6 whereas the total summed load is represented by Figure 7 with weekly configurations by season.

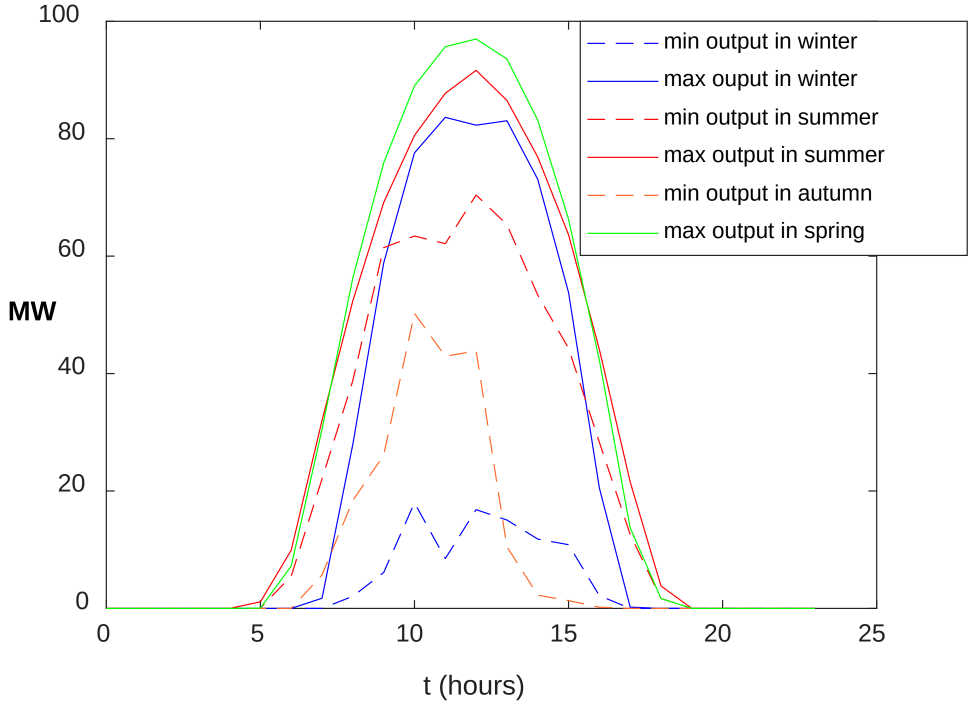


Figure 6 Daily generation range of PV output per season.

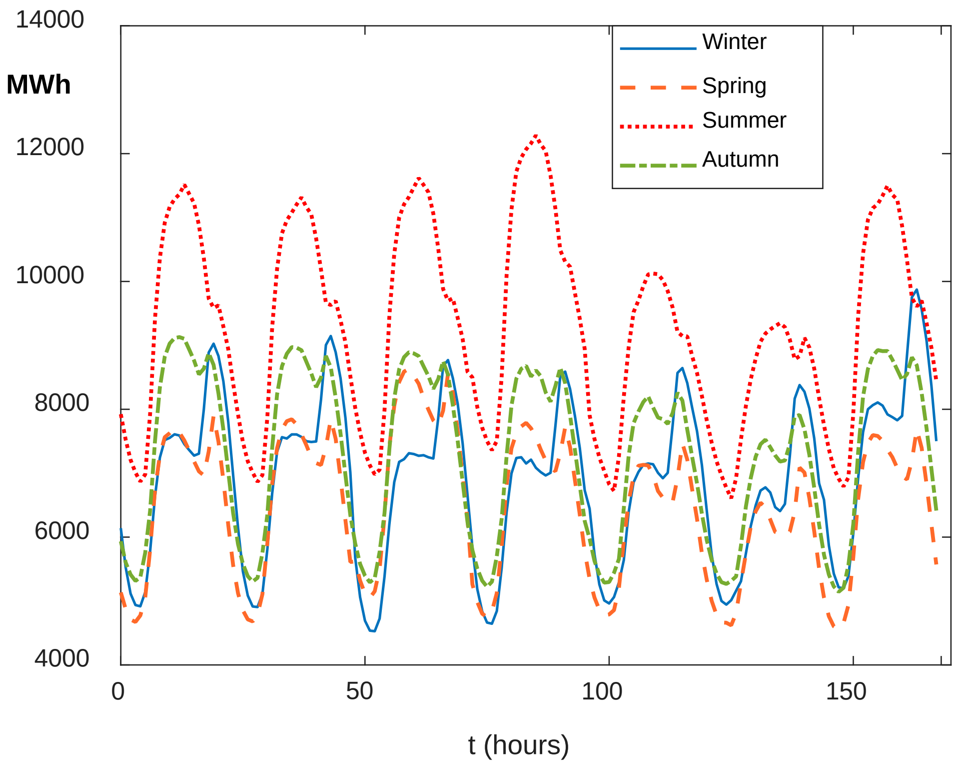


Figure 7 Hourly summed load demand per season.

3.2 Results and discussion

In order to perform weekly simulations for an entire year, the initial conditions are updated to relate each week with previous weekly schedules. As stated before, the maximum share of RES by the end of 2020 was 11.7%. To assess the efficacy of the power scheduling throughout the year, we consider two case studies, namely without and with electrical energy storage. Our purpose is to evaluate the imposed expenses due to load shedding, spinning reserve deficits and RES curtailment. In this regard, we penalize the respective parameters with 950€/MWh and 850€/MWh, while the RES producers receive a payback calculated by the average hourly summed fuel cost (F_t) derived from the conventional generating units $\sum_i \sum_t C_i^t$ over the daily net demand $\sum_t P_{NL}^t$. For each case study, we assume three scenarios which constitute: 1) the base case, 2) a 250% and 3) 500% increase in PV installations.

Taking a look at the results derived from the priority-list schemes, in the absence of storage we observe severe reliability violations with associated penalty expenses which increase in accordance with the increasing PV penetration share. Distinguishing the domestic resources into firm, variable and uncertain, we assign the values of $\xi 1=0$, $\xi 2=1$, $\xi 3=1$, for the biomass, PV and wind SR requirements. During the base case, the load shedding reaches 18MWh with 99MWh of curtailed RES and 6.136GWh of SR deficits. This corresponds to a PV hosting capacity of 3.84%. Varying the SR factors at the second scenario, the achieved hosting capacity approaches 6.84%, while a fair of 9.34% was observed during the third scenario. The derived results without the storage contribution for the assumed scenarios are illustrated in Table 2.

Table 2 Results concerning the test-case studies in the absence of storage.

Scenario	**ξ1**	**ξ2**	**ξ3**	**PV instal. increment**	**PV hosting capacity (%)**
Base	0	1	1	1	3.84
1	0	0.5	1	x2.5	6.84
2	0	0.2	1	x5	9.84

In the presence of storage, we assume a facility with cycling capability of 85% AC-to-AC efficiency and 1% of hourly SDR. Based on the weekly UC schedules, the penalty expenses of load shedding and RES curtailment are eliminated, whereas the SR deficits are minimized to account for 4.3MWh, 80.3MWh and 95.2MWh during the respective scenarios. Although the storage facilitates in SR minimization and RES enhancement by storing the energy during excess production and discharging during peak hours, the PV hosting capacity at the base case is limited to 3.49%. This is due to the total annual demand rise to satisfy the charging needs during the limited RES contribution in charging process. As the penetration levels increase, we obtain more sustainable schedules. The optimally sized, in terms of rated power and energy capacity (E_{cap}), storage medium offers greater PV hosting capacities which correspond to 9.62% and 19.25% during the second and third scenario of our evaluation.

The obtained results are tabulated in Table 3 along with the size of the supporting energy storage system. The new electricity demand in the presence of storage is demonstrated in Figures 8 and 9, where a cycle operation per season is presented.

Table 3 Results concerning the test-case studies in the presence of storage.

Scenario	**ξ1**	**ξ2**	**ξ3**	**PV instal. increment**	**PV hosting capacity (%)**	**Prated (MW)**	**Ecap (MWh)**
Base	0	1	1	1	3.49	87.3	218.1
1	0	0.5	1	x2.5	9.62	94.1	470.3
2	0	0.2	1	x5	19.25	305.7	2445

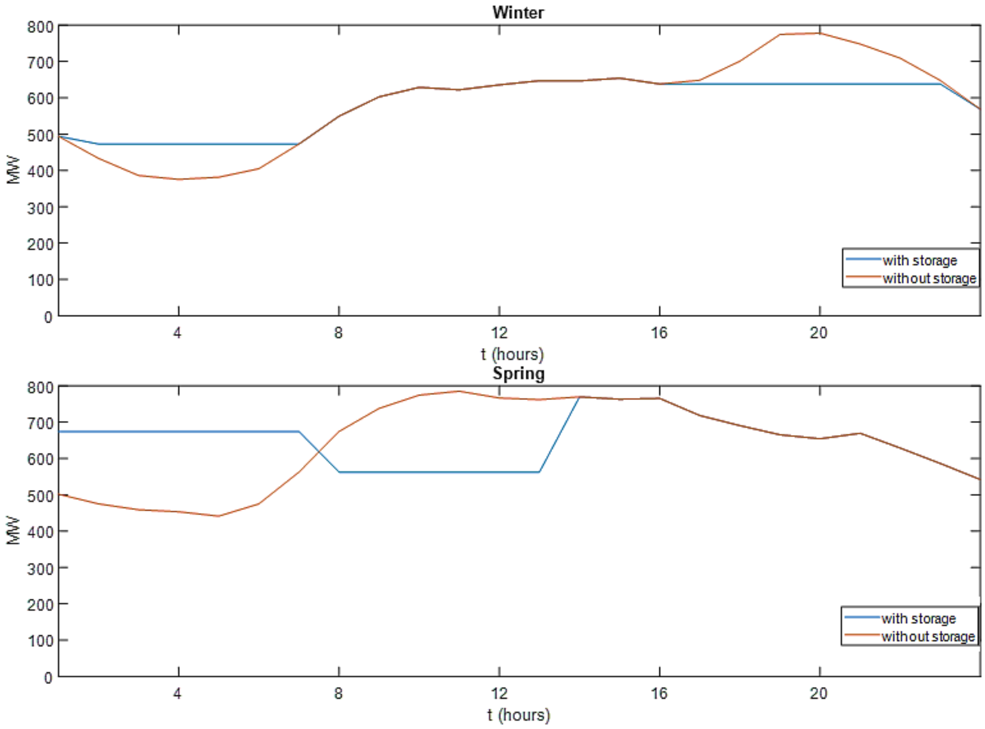


Figure 8 Representative winter and spring cycle operation of the applied storage system during Scenario 2.

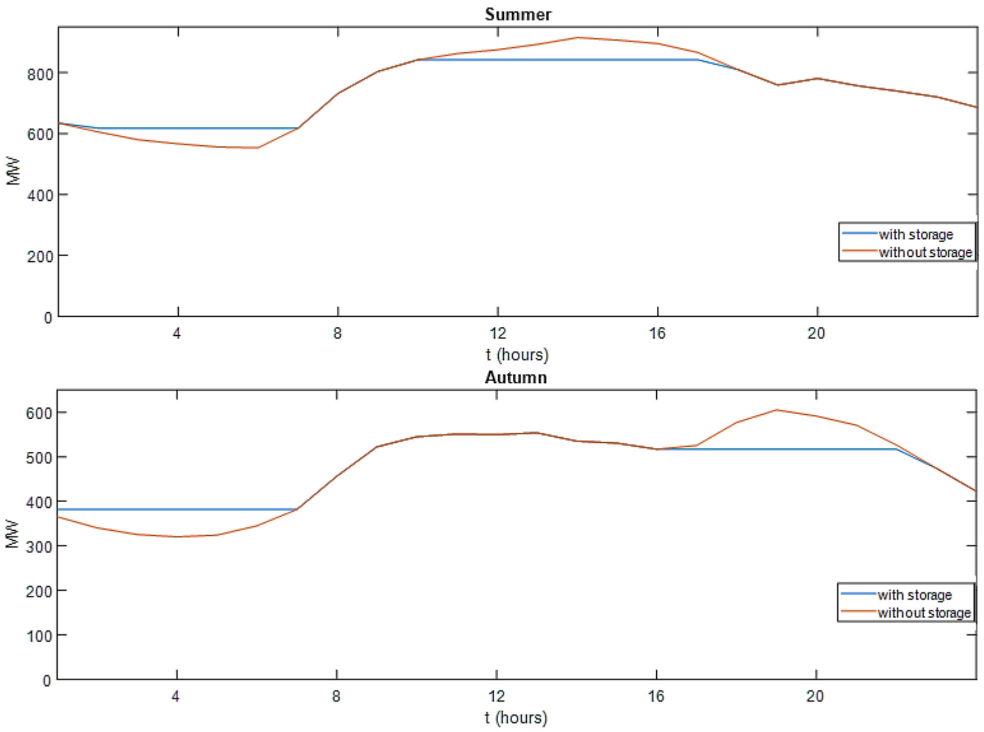


Figure 9 Representative summer and autumn cycle operation of the applied storage system during Scenario 2.

4. Conclusions

In this work, we provided the optimal unit commitment schedules and we defined the appropriate electricity storage size to evaluate the PV hosting capacity utilizing the advances of enhanced priority-list schemes. Based on actual data, the thermal generation of the power system of the island of Cyprus was investigated in the absence and presence of storage. The selected storage system possesses a cycle overall efficiency of 85% and 1% hourly self-discharge rate. Based on their classification, we assigned different spinning reserve factors for the domestic resources. Specifically, biomass was treated as a firm input, whereas PV and wind energy were assumed as variable and uncertain imports, respectively. Varying the PV installed capacity, the obtained results showed that improvements exist in terms of increased hosting capacity when electricity storage was integrated. The findings of our extensive evaluation are summarized as follows: 1) In the absence of storage the PV hosting capacity is limited by the reliability parameters of load shedding, curtailed renewable energy and spinning reserve deficits; 2) In the presence of storage, the share of distributed energy sources including photovoltaics decreases at low penetration levels; 3) Electricity storage is favoured at higher PV penetration levels where the enhanced 19.25% PV hosting capacity was achieved.

Our proposed solution based on enhanced priority-based technique can appropriately be applied also for microgrid formations consisted of different distributed energy resources and storage. The demonstrated outcome shows better performance in terms of both total production cost and associated emissions, inspiring system operators to better plan-ahead their power networks in a sustainable manner. This also motivates market participants who can benefit either by enhanced RES installations or storage provisions as operating reserves. Consequently, this work constitutes a powerful optimization tool which is capable of capturing the total benefits from RES and, relying on comprehensive UC formulations, can enrich the hosting capacity, not only in distribution networks but also in large-scale power systems. As for future directions to research, we indicate the examination of combined large-scale networks and microgrid formations of different size in islanded and interconnected operations. In addition, we propose the consolidation of storage cost parameters into the objective function to enable the optimally sized storage facility and definition of the best combination relating to diverse distributed resources.

Ethics Statement

Not applicable.

Availability of Data and Material

Not applicable.

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Competing Interests

Andreas Poullikkas is a member of the Editorial Board of the journal Green Energy and Sustainability. Pavlos Nikolaidis declares that he has no competing interests. The two authors were not involved in the journal's review of or decisions related to this manuscript.

Author Contributions

Pavlos Nikolaidis: Conceptualization, Investigation, Methodology, Software, Writing- Original draft preparation, Visualization.

Andreas Poullikkas: Conceptualization, Methodology, Data curation, Supervision.

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Abbreviations

The following abbreviations are used in this manuscript:

BES	Battery energy storage
DER	Distributed energy resources
ED	Economic dispatch
ES	Electricity storage
EU	European Union
HC	Hosting capacity
I.C.	Initial conditions
MD	Minimum down time
MU	Minimum up time
OPF	Optimal power flow
PHV	Plug-in electric vehicles
PV	Photovoltaic

RES	Renewable energy sources
RD	Ramp down rate
RU	Ramp up rate
SDR	Self-discharge rate
SR	Spinning reserves
SU	Start-up cost
UC	Unit commitment
VSWT	Variable speed wind turbines

References

1. Nikolaidis P, Chatzis S, Poullikkas A. Renewable energy integration through optimal unit commitment and electricity storage in weak power networks. Int. J. Sustain. Energy 2019; 38(4): 398-414. Available from: https://www.tandfonline.com/doi/abs/10.1080/14786451.2018.1516669.
2. Nikolaidis P, Fotiou S, Kasparis T, Poullikkas A. Dynamic analysis of high-response storage systems to minimize the generation ramping requirements. Proceedings of MEDPOWER2020; 9-12 Nov 2020; Paphos, Cyprus.; 14 Jan 2021. p. 1–6. Available from: https://medpower2020.org/program/.
3. Nikolaidis P, Poullikkas A. A comparative review of electrical energy storage systems for better sustainability. J. Power Technol. 2017; 97(3):220–245. Available from: http://papers.itc.pw.edu.pl/index.php/JPT/article/view/1096/776.
4. Nikolaidis P, Poullikkas A. Enhanced Lagrange relaxation for the optimal unit commitment of identical generating units. IET Gener. Transm. Distrib. 2020; 14(18):3920–3928. Available from: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-gtd.2020.0410.
5. Nikolaidis P, Chatzis S. Gaussian process-based Bayesian optimization for data-driven unit commitment. Int. J. Electr. Power Energy Syst. 2021; 130:106930. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0142061521001708.
6. Nikolaidis P, Poullikkas A. Cost metrics of electrical energy storage technologies in potential power system operations. Sustain. Energy Technol. Assess. 2018; 25:43–59. Available from: https://www.sciencedirect.com/science/article/abs/pii/S2213138817304563.
7. Nikolaidis P, Poullikkas A. Sustainable Services to Enhance Flexibility in the Upcoming Smart Grids. In: Stagner JA, Ting DSK, editors. Sustaining Resources for Tomorrow. Switzerland: Springer Nature; 2020. p. 245–274.
8. Nikolaidis P, Antoniades A, Chatzis S. A Bayesian Optimization Approach For The Robust Unit Commitment Of Identical

Generating Units. Proceedings of Medpower2020; 9-12 Nov 2020; Paphos, Cyprus.: Easy CRS; 14 Jan 2021. p. 1–6. Available from: https://medpower2020.org/program/.

9. Nikolaidis P, Partaourides H. A Model Predictive Control for the Dynamical Forecast of Operating Reserves in Frequency Regulation Services. Forecasting 2021; 3(1):228–241. Available from: https://www.mdpi.com/2571-9394/3/1/14.
10. Ismael SM, Abdel SHE, Abdelaziz AY, Zobaa AF. State-of-the-art of hosting capacity in modern power systems with distributed generation. Renew. Energy 2019; 130:1002–1020. Available from: https://www.sciencedirect.com/science/article/pii/S0960148118307936.
11. Ismael SM, Aleem SHEA. Practical Considerations for Optimal Conductor Reinforcement and Hosting Capacity Enhancement in Radial Distribution Systems. IEEE Access 2018; 6:27268–27277. Available from: https://ieeexplore.ieee.org/document/8360415.
12. Sakar S, Balci ME, Abdel SHE, Zobaa AF. Increasing PV hosting capacity in distorted distribution systems using passive harmonic filtering. Electr. Power Syst. Res. 2017; 148:74–86. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0378779617301207.
13. Mulenga E, Bollen MHJ, Etherden N. A review of hosting capacity quantification methods for photovoltaics in low-voltage distribution grids. Electr. Power Energy Syst. 2020; 115:105445. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0142061519306490.
14. Production E, Large N, Equipment C. Hosting Capacity of the Power Grid for Renewable Electricity Production and New Large Consumption Equipment. Energies 2017; 10(9):1325. Available from: https://www.mdpi.com/1996-1073/10/9/1325.
15. Papaefthymiou SV, Karamanou EG, Papathanassiou SA, Papadopoulos M.P. A Wind-Hydro-Pumped Storage Station Leading to High RES Penetration in the Autonomous Island System of Ikaria. IEEE Trans. Sustain. Energy 2010; 1(3):163–172. Available from: https://ieeexplore.ieee.org/document/5512672.
16. Fernández-muñoz D, Pérez-díaz JI. Unit commitment in a hybrid diesel/wind/pumped-storage isolated power system considering the net demand intra-hourly variability. IET Renew. Power Gener. 2021; 15(1):30–42. Available from: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/rpg2.12003.
17. Villalba I, Blanco M. Lafoz M. Wave farms grid code compliance in isolated small power systems. IET Renew. Power Gener. 2019; 13(1):171–179. Available from: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-rpg.2018.5351.
18. Penetration R, Study C, Hierro E, Mart S, Ochoa D. Analysis of the Implementation of the Primary and/or Inertial Frequency Control in Variable Speed Wind Turbines in an Isolated Power System with

High Renewable Penetration. Case Study: El Hierro Power System. Electronics 2020; 9(6):901. Available from: https://www.mdpi.com/2079-9292/9/6/901.

19. Sarasúa JI, Martínez-Lucas G, Pérez-Díaz JI, Fernández-Muñoz D. Alternative operating modes to reduce the load shedding in the power system of El Hierro Island. Int. J. Electr. Power Energy Syst. 2021; 128:106755. Available from: https://www.sciencedirect.com/science/article/pii/S0142061520343003.
20. Fernández-Muñoz D, Pérez-Díaz JI. Contribution of non-conventional pumped- storage hydropower plant configurations in an isolated power system with an increasing share of renewable energy. IET Renew. Power Gener. 2020; 14(4):658–670. Available from: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-rpg.2019.0874.
21. Psarros GN, Kokkolios SP, Papathanassiou SA. Centrally Managed Storage Facilities in Small Non-Interconnected Island Systems. Proceedings of 53rd International Universities Power Engineering Conference (UPEC); 4-7 Sep 2018; Glasgow, UK. IEEE *Xplore*: IEEE; 22 Nov 2018. pp. 1–6.
22. Psarros GN, Papathanassiou SA. Evaluation of battery-renewable hybrid stations in small-isolated systems Evaluation of battery-renewables hybrid stations in small isolated systems. IET Renew. Power Gener. 2019; 14(1):39–51. Available from: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-rpg.2019.0212.
23. Psarros GN, Papathanassiou SA. Comparative Assessment of Priority Listing and Mixed Integer Linear Programming Unit Commitment Methods for Non-Interconnected Island Systems. Energies 2019; 12(4):667. Available from: https://www.mdpi.com/1996-1073/12/4/657.
24. Psarros GN, Papathanassiou SA. A Unit Commitment Method for Isolated Power Systems employing Dual Minimum Loading Levels to Enhance Flexibility. Electr. Power Syst. Res. 2019; 177:106007. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0378779619303268.
25. Abujarad SY, Mustafa MW, Jamian JJ. Recent approaches of unit commitment in the presence of intermittent renewable energy resources : A review. Renew. Sustain. Energy Rev. 2017; 70:215–223. Available from: https://www.sciencedirect.com/science/article/abs/pii/S1364032116310140.
26. Muralikrishnan N, Jebaraj L. A Comprehensive Review on Evolutionary Optimization Techniques Applied for Unit Commitment Problem. IEEE Access 2020; 8(20):132980–133014. Available from: https://ieeexplore.ieee.org/document/9144190.
27. Nikolaidis P, Chatzis S, Poullikkas A. Optimal planning of electricity storage to minimize operating reserve requirements in an isolated

island grid. Energy Syst. 2019; 11:1157–1174. Available from: https://link.springer.com/article/10.1007/s12667-019-00355-x.

28. Georgiou GS, Nikolaidis P, Kalogirou SA, Christodoulides P. A Hybrid Optimization Approach for Autonomy Enhancement of Nearly-Zero-Energy Buildings Based on Battery Performance and Artificial Neural Networks. Energies 2020; 13(14):3680. Available from: https://doi.org/10.3390/en13143680.
29. Elsayed AM, Maklad AM, Farrag SM. A New Priority List Unit Commitment Method for Large-Scale Power Systems. Proceedings of Nineteenth International Middle East Power Systems Conference (MEPCON); 18-20 Dec 2018; Cairo, Agypt. IEEE *Xplore*: IEEE; 07 Feb 2019. pp. 359–367.
30. Cyprus Energy Regulatory Authority. Annual Report of Cyprus Energy Regulatory Authority 2020. Online: CERA; [cited 2020 Jun 01]. 59. Report No.: Available from: https://www.cera.org.cy/en-gb/raek/details/etisia-ek8esi.

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