The Role of Flexibility Resources in the Energy Transition

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Abstract: Extremely adaptable power systems are required, as the share of variable renewable energy sources increases. The variable renewable energy sources' ability to be installed on the grid, is frequently thought to be constrained by a limited flexible capacity. A general, methodological framework, for the optimal scheduling of an islanded power system, with a variety of flexibility resources, is presented in this work. In particular, it takes into account a significant amount of intermittent RES and the widespread use of electric vehicles that offer charging and discharging options. The modeling in this work also considers demand response programs' active market participation and the installation of energy storage capacities. Additionally, it covers the involvement of electricity interconnections, as a source of flexibility. Two illustrative case studies of an island power system connected to a mainland power system, have been used, to evaluate the applicability of the proposed strategy. The scheduling framework is daily, with an hourly interval. The results of the modeling show how important all of the flexibility resources are, for effective energy management and the supply of ancillary services, especially in cases for high-RES penetration. The proposed method can be used by market operators, policymakers and regulatory authorities, to choose the best system development, market design and portfolio synthesis.

Keywords: optimization; island system; flexibility; interconnection; energy storage; demand response

1 Introduction

The availability of domestic energy resources and/or their importing options via available transportation means, the system-wide energy requirements that must be met, and the applied energy policy decision-making based on a series of factors such as economic, historical, social, environmental, demographic, institutional and/or geopolitical ones, are the key factors that determine the synthesis of the energy supply mix for each energy system. Especially recently, the issue of energy security has been gaining importance, both with regard to the availability of primary energy sources and the reliability of power systems in relation to the growing share of volatile renewable sources.

The rapidly growing share of electricity generation plants, based on volatile RES, together with the changes in the structure and functioning of the energy sector, brought about by progressive decarbonization, among other things, increase the importance of modeling the further development of energy systems. One of the key aspects of modeling is the issue of "generation adequacy", i.e., the search for such an arrangement of the electricity system structure (system elements, internal links between them, and links of the system to surrounding systems) that ensures energy security both in terms of short-term operation of the system (reliability of electricity supply) and in terms of long-term development of the energy system [1].

A series of works have been presented in the literature investigating the combined optimization of energy and reserves, dealing with the various aspects of generation adequacy and energy security. [2] highlights the increasing complexity of models reflecting the changing structure of the electricity industry, as a sector and a range of new constraints and target values. At the same time, [2] points out that models are often based on different assumptions, using different modeling approaches. This in turn, often leads to a wide dispersion of modeling results and the results of different models are often difficult to compare. In relation to this, it emphasizes the transparency of the description of the models, the assumptions used, and the modelling techniques. For example, [3] compares nine power sector models. Similar to [2], it highlights the differences between the models, both in the application of various constraints and in terms of the data used. In particular, they highlight differences in the ways in which the impact of EVs, pumped storage and demand response are captured. A survey of modeling techniques and trends in the co-optimization of the energy and reserves markets was provided by the authors in [4]. In [5], the authors formulated two approaches for clearing the energy and spinning reserve markets while examining the effects of demand involvement in the reserve offers. Investigation on the impact of demand flexibility on the clearing of the energy and reserves markets can be found in [6]. The thermal unit commitment problem has been studied through a mixed-integer linear programming (MILP) model in [7]. A version with a comparable unit commitment has also been given in [8]. A co-optimization strategy for energy-reserve power markets has been introduced in [9]. The authors of [10] presented a MILP model for the joint clearance of energy and reserve power exchanges by integrating the hourly offers module of EUPHEMIA (pan-EUroPean Hybrid Electricity Market Integration Algorithm) with particular unit commitment constraints. Additionally, the same authors in [11] studied the market products offered by EUPHEMIA for the interconnected Greek electricity grid. In addition, the authors of [12] created an optimization model for deciding how to dispatch energy and reserves in electricity markets. The authors of [13] developed a methodological approach for integrating bidding schemes, in day-ahead energy and spinning reserve markets, focusing on the bidding strategies. For a generation business to optimize its economic profit in day-ahead energy and spinning reserve markets, the authors in [14] devised an optimization model for the optimal bidding strategy problem. The authors in [15], focused on islanded power systems and underscored the role that electricity interconnection plays in meeting reserve requirements.

This paper proposes an optimization approach for the optimal scheduling of energy and reserves for an island power system, taking into account the involvement of thermal power plants, renewable energy sources, an energy storage system, electric vehicles, and demand response initiatives (DRPs). The work's consideration of the activation of electricity interconnections as a provider of flexibility services is a significant contribution. The mathematical model will be used to make operational decisions on the examined power system's energy generation mix, reserve provision mix, and quantification of flexibility provided by ESS, EVs, DRPs, and electricity interconnection.

The remaining parts of this paper are arranged as follows: The problem to be solved is defined in Section 2, and the mathematical model's explanation is provided in detail. Section 3 also provides a description of the case study and the relevant input data, and Section 4 provides a comprehensive discussion of the model outputs to highlight the main findings. Last but not least, Section 5 provides a summary of the primary conclusions.

2 Methodology

2.1 Objective Function

The optimization model co-optimizes the energy and reserves scheduling of an island that is interconnected with the mainland power system from the system operator's perspective. A flowchart of the proposed methodological approach is depicted in Figure 1.

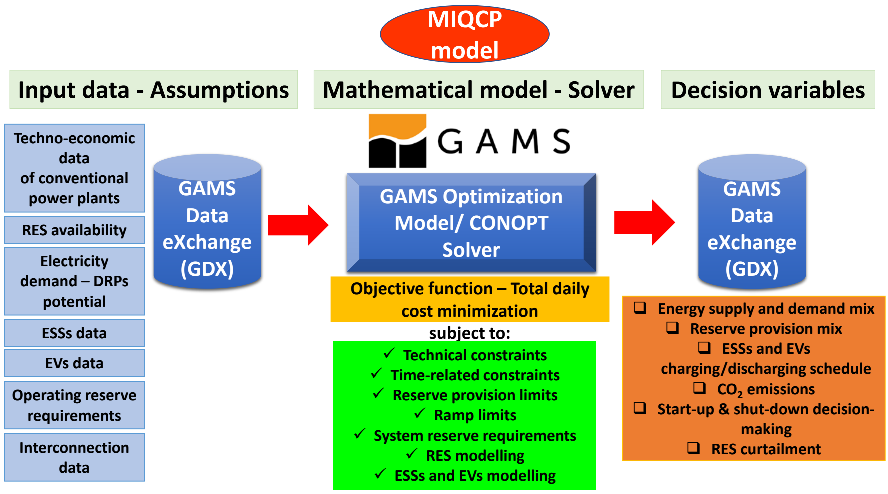

Figure 1
Superstructure of the proposed methodological approach

The mathematical model's objective function to be minimized refers to the net daily cost (1), including the following components:

(i) Electricity production cost of installed diesel-fired power generators

(ii) Start-up costs of diesel-fired power generators

(iii) RES curtailment cost

(iv) Operating reserve-up and -down provision cost

$$MinC^{oper} = \overbrace{\sum_i \sum_t C_{i,t}^{prod}}^{\substack{Energy\ supply\ cost \\ from\ thermal\ power\ units}} + \overbrace{\sum_i \sum_t C_i^{stup} \cdot y_{i,t}}^{\substack{Thermal\ power\ units \\ start-up\ cost}} + \overbrace{\sum_r \sum_t C_{r,t}^{curt} \cdot p_{r,t}^{curt}}^{RES\ curtailment\ cost} + \overbrace{\sum_n \sum_t C_{n,t}^{up} \cdot r_{n,t}^{up}}^{Reserve\ up\ cost} + \overbrace{\sum_m \sum_t C_{m,t}^{dn} \cdot r_{m,t}^{dn}}^{Reserve\ down\ cost} \qquad (1)$$

2.2 Electricity Supply and Demand Balance

The energy demand balance of the studied islanded power system is formulated in Equation (2). More specifically, the electricity supply from diesel-fired power generators ($\sum_i p_{i,t}^{conv}$), renewable energy sources ($\sum_r p_{r,t}^{res}$), power discharge from ESSs ($\sum_w p_{w,t}^{dis}$) and EVs ($\sum_v p_{v,t}^{dis} \cdot n_v^{tot}$), and electricity imports from the mainland power system (imp_t) must satisfy the final electricity demand after potential activation of demand response programs ($\sum_y d_{y,t}^{cl}$), the electricity exports to the mainland power system (exp_t) and the charging requirements from both ESSs ($\sum_w p_{w,t}^{ch}$) and EVs ($\sum_v p_{v,t}^{ch} \cdot n_v^{tot}$) in each time interval.

$$\begin{aligned}&\sum_i p_{i,t}^{conv} + \sum_r p_{r,t}^{res} + \sum_v p_{v,t}^{dis} \cdot n_v^{tot} + \sum_w p_{w,t}^{dis} \\ &+imp_t = \sum_y d_{y,t}^{cl} + \sum_v p_{v,t}^{ch} \cdot n_v^{tot} + \sum_w p_{w,t}^{ch} + exp_t\end{aligned} \qquad \forall t \ (2)$$

2.3 Technical Constraints

The production cost of each diesel-fired power generator ($C_{i,t}^{prod}$) is calculated by Equation (3), and is a function of its electricity output ($p_{i,t}^{conv}$) and its specific cost coefficients (a_i, b_i, and c_i). The operational range of each diesel-fired power generator, both maximum ($\mathrm{P_i^{max}}$) and minimum ($\mathrm{P_i^{min}}$), is bounded by constraints (4) and (5). Both constraints take into account the power unit's participation in energy ($p_{i,t}^{conv}$) and reserves-up ($r_{i,t}^{up}$) and down ($r_{i,t}^{dn}$) scheduling, subject also to the decision of its operation or not ($x_{i,t}^{oper}$). Furthermore, constraints (6) and (7) set the ramp limits, both up (RU_i) and down (RD_i), of each diesel-fired power generator. In addition, Constraint (8) determines the minimum uptime (UT_i) of each diesel-fired power generator after its start-up decision ($y_{i,t}$), as well as Constraint (9), describes the minimum downtime (UT_i) of each diesel-fired power generator after its shut-down decision ($z_{i,t}$). Finally, Equation (10) is a logical one, correlating operation, start-up, and shut-down decision-making.

$$C_{i,t}^{prod} = a_i \cdot (p_{i,t}^{conv})^2 + b_i \cdot p_{i,t}^{conv} + c_i \qquad \forall i,t \ (3)$$

$$p_{i,t}^{conv} + r_{i,t}^{up} \leq P_i^{max} \cdot x_{i,t}^{oper} \qquad \forall i,t \ (4)$$

$$p_{i,t}^{conv} - r_{i,t}^{dn} \geq P_i^{min} \cdot x_{i,t}^{oper} \qquad \forall i,t \ (5)$$

$$\left(p_{i,t}^{conv} + r_{i,t}^{up}\right) - (p_{i,t-1}^{conv} - r_{i,t-1}^{dn}) \leq RU_i \qquad \forall i,t \ (6)$$

$$\left(p_{i,t-1}^{conv} + r_{i,t-1}^{up}\right) - (p_{i,t}^{conv} - r_{i,t}^{dn}) \leq RD_i \qquad \forall i,t \ (7)$$

$$\sum_{t'=t-UT_i+1}^{t} y_{i,t'} \leq x_{i,t}^{oper} \qquad \forall i,t \; (8)$$

$$\sum_{t'=t-DT_i+1}^{t} z_{i,t'} \leq 1 - x_{i,t}^{oper} \qquad \forall i,t \; (9)$$

$$y_{i,t} - z_{i,t} = x_{i,t}^{oper} - x_{i,t-1}^{oper} \qquad \forall i,t \; (10)$$

2.4 RES Modeling

The upper production potential of each RES in each time interval ($F_{r,t}$) is imposed by Constraint (11). In particular, it equals the amount that is directly utilized ($p_{r,t}^{res}$) and the other one that is curtailed ($p_{r,t}^{curt}$). Furthermore, Constraint (12) sets a maximum limit on the reserve-down supply potential of each RES in each time interval ($r_{r,t}^{dn}$).

$$p_{r,t}^{res} + p_{r,t}^{curt} \leq F_{r,t} \qquad \forall r,t \; (11)$$

$$p_{r,t}^{res} - r_{r,t}^{dn} \geq 0 \qquad \forall r,t \; (12)$$

2.5 Electricity Exchanges Modeling

The energy and reserve exchanges with the mainland power system are formulated in Constraints (13)-(16). More specifically, Constraint (13) sets the maximum value (IMP_t^{cap}) of electricity imports (imp_t) and operating reserve-up (r_t^{up}) supply from the mainland power system. In the same context, Constraint (14) describes the respective upper capability of reserve-down provision (r_t^{dn}). Last but not least, Constraints (15) and (16) set the corresponding limits for the case of electricity exports and reserve exchanges to the mainland power system.

$$imp_t + r_t^{up} \leq IMP_t^{cap} \qquad \forall t \; (13)$$

$$imp_t - r_t^{dn} \geq 0 \qquad \forall t \; (14)$$

$$exp_t + r_t^{dn} \leq EXP_t^{cap} \qquad \forall t \; (15)$$

$$exp_t - r_t^{up} \geq 0 \qquad \forall t \; (16)$$

2.6 ESSs Modeling

Constraint (17) quantifies the state-of-charge balance level of each ESS in each time interval. ($soc_{w,t}^{st}$), considering both charging (SF_w^{ch}) and discharging efficiencies (SF_w^{dis}) for charging ($p_{w,t}^{ch}$) and discharging ($p_{w,t}^{dis}$) modes, correspondingly.

Moreover, the upper charging (G_w^{ch-max}) and discharging limits ($G_w^{dis-max}$) of each ESS are expressed by Constraints (18) and (19), respectively, considering its participation in both energy ($p_{w,t}^{ch}$ and $p_{w,t}^{dis}$) and reserve ($r_{w,t}^{dn}$ and $r_{w,t}^{up}$) markets. Also, constraints (20) and (21) guarantee that ESS energy level and reserve schedules are within the allowable bounds, both minimum (SOC_w^{min}) and maximum (SOC_w^{max}), respectively.

$$soc_{w,t}^{st} = soc_{w,t-1}^{st} + p_{w,t}^{ch} \cdot SF_w^{ch} - \frac{p_{w,t}^{dis}}{SF_w^{dis}} \qquad \forall w, t \ (17)$$

$$p_{w,t}^{ch} + r_{w,t}^{dn} \leq G_w^{ch-max} \qquad \forall w, t \ (18)$$

$$p_{w,t}^{dis} + r_{w,t}^{up} \leq G_w^{dis-max} \qquad \forall w, t \ (19)$$

$$soc_{w,t}^{st} - \frac{r_{w,t}^{up}}{SF_w^{dis}} \geq SOC_w^{min} \qquad \forall w, t \ (20)$$

$$soc_{w,t}^{st} + r_{w,t}^{dn} \cdot SF_w^{ch} \leq SOC_w^{max} \qquad \forall w, t \ (21)$$

2.7 EVs Modeling

The corresponding EV modeling is formulated analogously to the ESS one by Constraints (22-26). More specifically, Equation (22) sets the state-of-charge level in each time interval ($soc_{v,t}^{ev}$), as well as constraints (23) and (24) impose the maximum limits on charging (G_v^{ch-max}) and discharging decision-making (G_v^{ch-max}), taking into account their involvement in both energy and reserve markets. Finally, constraints (25) and (26) guarantee that EV energy levels and reserve schedules are within specific imposed energy limits.

$$soc_{v,t}^{ev} = soc_{v,t-1}^{ev} + p_{v,t}^{ch} \cdot SF_v^{ch} \cdot n_v^{tot} - \frac{\left(p_{v,t}^{dis} + E_{v,t}^{cons}\right)}{SF_v^{dis}} \qquad \forall v, t \ (22)$$

$$p_{v,t}^{ch} + r_{v,t}^{dn} \leq G_v^{ch-max} \qquad \forall v, t \ (23)$$

$$p_{v,t}^{dis} + r_{v,t}^{up} \leq G_v^{dis-max} \qquad \forall v, t \ (24)$$

$$soc_{v,t}^{ev} - \frac{r_{v,t}^{up}}{SF_v^{dis}} \geq SOC_v^{min} \qquad \forall v, t \ (25)$$

$$soc_{v,t}^{ev} + r_{v,t}^{dn} \cdot SF_v^{ch} \leq SOC_w^{max} \qquad \forall v, t \ (26)$$

2.8 DRPs Modeling

Constraints (27-30) formulate the DRPs modeling. In particular, Equation (27) describes the amount of the modified energy demand ($d_{y,t}^{cl}$), taking into account the applied DRPs ($d_{y,t}^{up}$ and $d_{y,t}^{dn}$) upon the reference electricity demand ($D_{y,t}^{ref}$).

Equation (28) ensures that the total energy demand is at the same levels over the scheduling time horizon. Finally, constraints (29-30) set the minimum ($D_{y,t}^{min}$) and maximum ($D_{y,t}^{max}$) demand variation ranges, respectively.

$$d_{y,t}^{cl} = D_{y,t}^{ref} + d_{y,t}^{up} - d_{y,t}^{dn} \qquad \forall y, t \quad (27)$$

$$\sum_t d_{y,t}^{up} = \sum_t d_{y,t}^{dn} \qquad \forall y \quad (28)$$

$$d_{y,t}^{cl} - r_{y,t}^{up} \geq D_{y,t}^{min} \qquad \forall y, t \quad (29)$$

$$d_{y,t}^{cl} + r_{y,t}^{dn} \leq D_{y,t}^{max} \qquad \forall y, t \quad (30)$$

2.9 System Reserve Requirements

Constraints (31) and (32) determine the system operating reserve requirements in both upward (R_t^{up}) and downward (R_t^{dn}) directions, respectively.

$$\sum_i r_{i,t}^{up} + \sum_w r_{w,t}^{up} + \sum_v r_{v,t}^{up} + \sum_y r_{y,t}^{up} + r_t^{up} \geq R_t^{up} \qquad \forall t \quad (31)$$

$$\sum_i r_{i,t}^{dn} + \sum_w r_{w,t}^{dn} + \sum_v r_{v,t}^{dn} + \sum_y r_{y,t}^{dn} + \sum_r r_{r,t}^{dn} + r_t^{dn} \geq R_t^{dn} \qquad \forall t \quad (32)$$

The objective function (1) to be minimized is included in the overall optimization problem, which is expressed as a mixed-integer quadratically constrained programming problem that is subject to the imposed constraints and equations (2)-(32).

3 Case Study

The developed optimization model has been tested on an illustrative case study of an islanded power system. In particular, the four diesel-fueled power units of the chosen islanded power system are detailed in their techno-economic characteristics in Tables 1 and 2. These data include the start-up cost, the technical minimums and maximums, the ramp limits, and the minimum uptimes and downtimes for each diesel-fired unit.

Wind turbines account for 200 MW, and solar photovoltaics for the remaining 80 MW of the 280 MW installed capacity in addition to the diesel-fueled generators. The daily reference electricity demand and the RES potential for each technology type over each time period are depicted in Figure 2.

Table 1
Economic data of the studied power system

Diesel-fired generator *i*	**a (€/MW²)**	**b (€/MW)**	**c (€)**	**Start-up cost (€)**
Diesel-1	3	20	100	50000
Diesel-2	4.05	18.07	98.87	50000
Diesel-3	3.99	19.21	107.2	50000
Diesel-4	3.88	26.18	95.31	50000

Table 2
Technical data of the studied power system

Diesel-fired generator *i*	**Technical minimum (MW)**	**Technical maximum (MW)**	**Ramp-up and down (MW/min)**	**Minimum uptime (h)**	**Minimum downtime (h)**
Diesel-1	28	150	4	16	1
Diesel-2	20	120	3	16	1
Diesel-3	30	100	3	16	1
Diesel-4	20	200	5	16	1

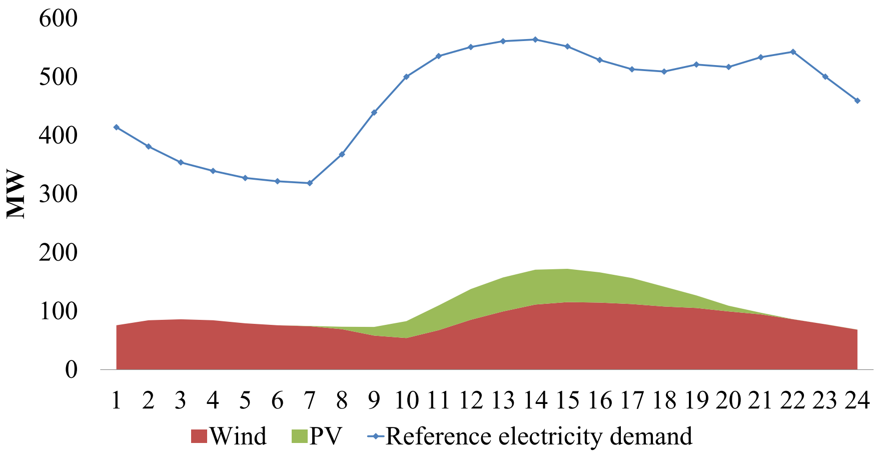

Figure 2
Reference electricity demand and RES potential per technology type in each time period

The battery capacity, the initial energy storage level, the charging and discharging efficiencies, the minimum allowable energy storage level, and the charging and discharging rates of the ESS considered are all shown in Table 3.

Table 3

ESS operational data

ESS data	Value
Battery capacity (MWh)	50
Initial storage level (MWh)	25
Charging efficiency (%)	0.95
Discharging efficiency (%)	0.9
Minimum battery energy storage level (MWh)	5
Charging rate (MW)	50
Discharging rate (MW)	50

Table 4 presents the operational data of the considered EVs, including the number of EVs (1000 in total), the battery capacity, the charging and discharging efficiencies, as well as the charging and discharging rates. Each electric vehicle is assumed to have a minimum energy storage level equal to 10% of its battery capacity, and the initial energy storage level at hour "0" is assumed to be 50% of its battery capacity. Figure 3 presents the EVs' electricity consumption allocation for the trips conducted during the examined day.

Table 4

EVs techno-economic data

Electric vehicle type	Number of electric vehicles	Charging, discharging efficiency (%)	Charging, discharging power (MW)	Battery capacity (MWh)
EV-1	300	95	0.0072	0.0173
EV-2	50	95	0.011	0.1
EV-3	250	95	0.0037	0.0076
EV-4	150	95	0.0046	0.0358
EV-5	250	95	0.0037	0.023

In both directions, the reserve requirements are assumed to be 20% of the reference electricity demand. Diesel-fired generating units will receive a reserve provision price of 10 €/MW, ESS of 12 €/MW, EVs of 15 €/MW, the grid will receive 20 €/MW, and DRPs will receive 25 €/MW.

Lastly, the electricity interconnection capacity with the mainland power system in both directions is assumed to be 250 MW.

An additional case study ("Energy transition case") has been executed to assess the case where RES more than cover the expected electricity load. In particular, the installed capacity of both wind and solar power is assumed to be 1000 MW each. Moreover, the battery storage capacity increases to 1000 MWh with the same techno-economic data as in the reference case. Finally, the reserve provision price of all providers (diesel-fired units, ESS, EVs, DRPs, RES) is assumed to be 10 €/MW.

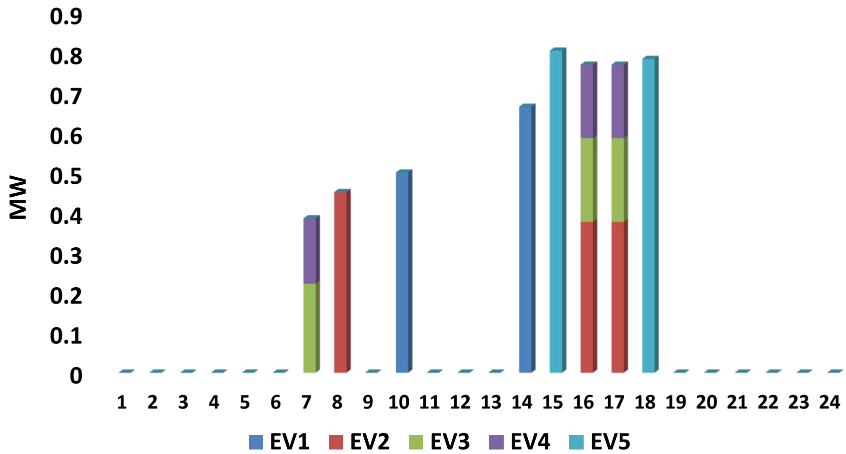

Figure 3
EVs electricity consumption on an hourly basis

4 Results and Discussion

The problem has been globally optimized using the CONOPT solver within the General Algebraic Modeling System (GAMS) Studio 37 [16]. An optimality gap of 0% has been achieved.

4.1 Reference Case

The total daily operating cost of the islanded power system amount to around 1.77 million €. This value is quite important when compared to the case where there is no electricity interconnection with the mainland power system, where the corresponding number equals around 3.1 million €. The net cost of purchasing electricity makes up 71% of the 1.77 million euros; the remaining cost is split between the generation cost of diesel-fired units (26%) and the cost of providing reserves (3%). The energy supply and demand mix of the analyzed islanded power system is shown in Figure 4 on an hourly basis. With their charging and discharging cycles, ESSs and EVs make energy allocation easier for several hours a day. The main charging hours for ESSs are the 6th and the 24th hours, as well as the EVs are being charged during the 1st day hour and the time interval between hours 3-5.

ESSs discharge during the 1st and the 8th day hours, and the EVs during 8th, 9th and 22nd day hour. There is also a model assumption that the storage levels at both ESSs and EVs must remain unchanged between the beginning (hour "0") and the end (hour "24") of the examined day. Figure 5, which depicts the daily allocation of energy supply, demonstrates that the grid's net imports share accounts for nearly 49% of the total supply, followed by diesel-fired generators, which stand for 28%, and RES, whose share represents the remaining 23%. In the case of the absence of electricity interconnection with the mainland power system, diesel-fired power generators meet around 77% of the total electricity contribution, and the remaining 23% is supplied by RES power units.

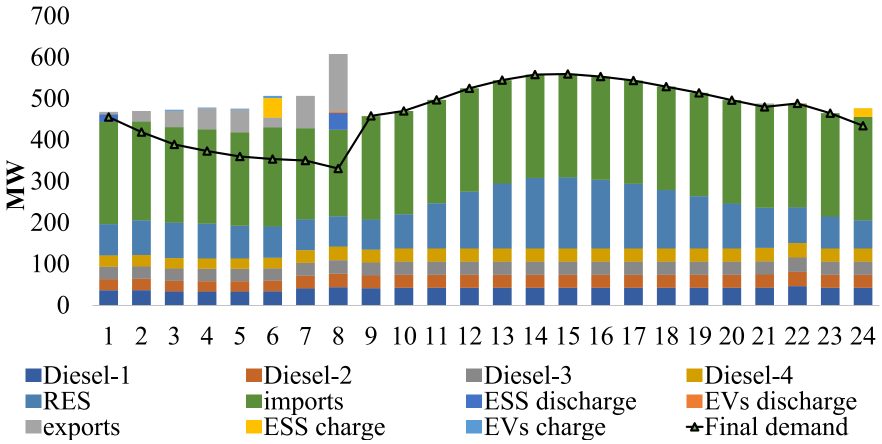

Figure 4
Hourly energy supply and demand mix of the examined islanded power system

The operating-up reserve provision mix of the analyzed islanded power system is depicted in Figure 6. Diesel-fired generators are the only ones providing this service, and they are regarded as the most cost-effective means of doing so. Figure 7 depicts how they operate close to their technical minimums and remain operational throughout the day. As a result, they may be able to provide this upward service by increasing their power output. This is also the case in the scenario without electricity interconnection with the mainland power system, where the diesel-fired power generators operate between 52% and 67% of their technical maximums, as depicted in Figure 8. Thus, there is enough capacity to provide, that upward service, during all of the day hours.

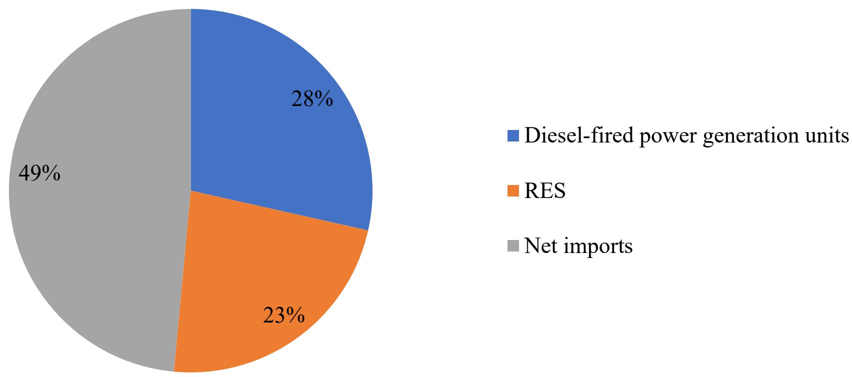

Figure 5
Daily energy supply allocation of the examined islanded power system

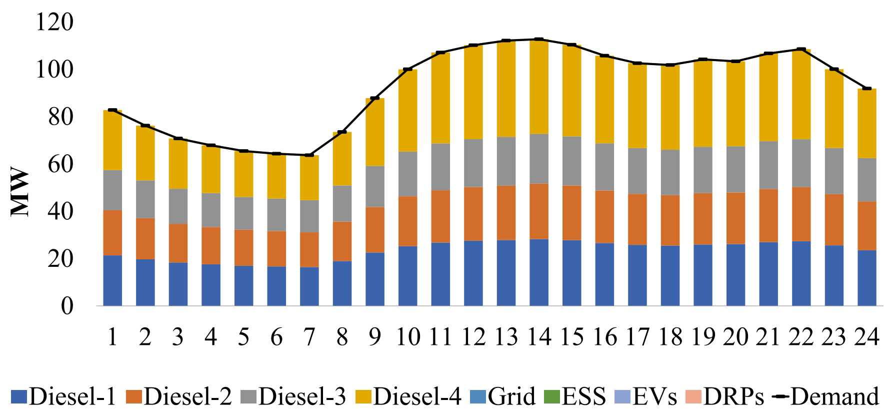

Figure 6
Operating-up reserve provision mix of the examined islanded power system

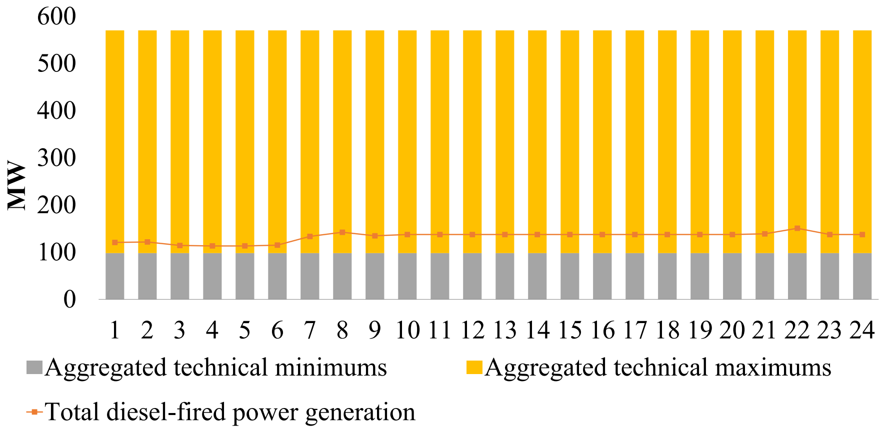

Figure 7
Hourly diesel-fired power generation of the examined islanded power system in the case of electricity interconenction with the mainland power system

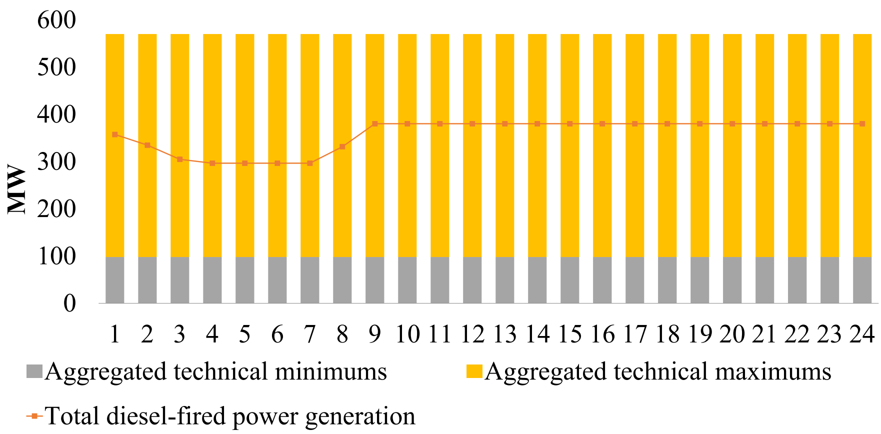

Figure 8
Hourly diesel-fired power generation of the examined islanded power system in the case of no electricity interconenction with the mainland power system

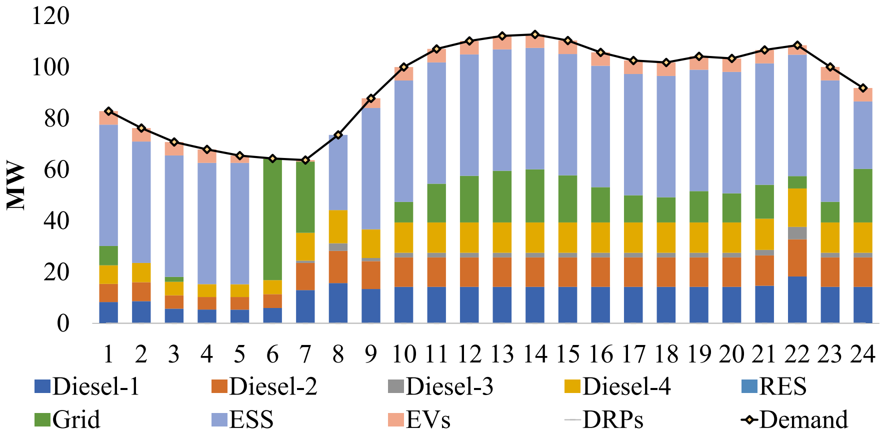

Figure 9

Operating-down reserve provision mix of the examined islanded power system

The operating-down reserve provision mix of the analyzed islanded power system is depicted in Figure 9. On a daily basis, the ESS meets 45% of that service's total requirements. Diesel-fired units account for approximately 37% of total requirements, while EVs cover almost 5% of daily requirements. It is important to note that the electricity interconnection with the power system on the mainland contributes to the service's coverage, providing approximately 13% of the total daily requirements. Note that due to the fact that the diesel-fired power units operate at medium levels in the case of no electricity interconnection with the mainland power system (see Figure 7), they have increased capability to provide also downward service. In particular, they cover the whole daily needs in that case.

The modified and reference electricity demands of the studied islanded power system are shown in Figure 10. Although the total daily load remains unchanged, there are distinct patterns in the allocation of the hourly electricity demand. During the hours when the net reference electricity demand is at its lowest, the modified electricity demand is characterized by some increases compared to the reference demand. These times are between 1 and 7 hours, 9 hours, and 15 to 18 hours. During specific hours, namely 8th, 10th-14th and 19th-24th, the modified electricity demand decreases somewhat in comparison to the reference. The model determines the best scheduling strategy to reduce these peak periods of the net reference electricity demand in order to satisfy the net load at a more cost-effective rate. The results are almost identical when the electricity interconnection, with the mainland power system, is not included.

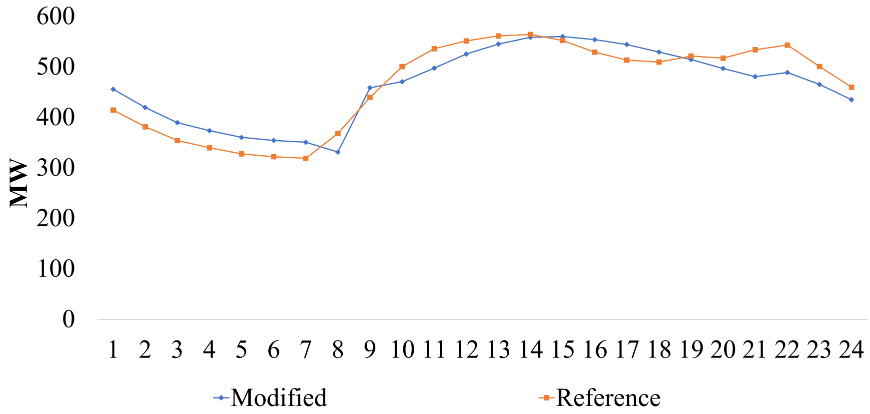

Figure 10
Modified and reference electricity demand of the examined islanded power system

Figure 11 portrays the state-of-charge levels of each EV type of the examined islanded power system. It is assumed in the case study adopted that the storage level at the time period prior to the optimization process (hour "0") and the last day hour, namely the 24th one, must remain the same and amount to 50% of the aggregated battery capacity of each EV type. It can be observed that the 6th and 7th hours comprise the ones where the battery capacities are almost full for all EV types, and they gradually discharge, either selling electricity to the grid or using it for their consumption for the conduction of their trips, to reach the 50% level at the end of the day.

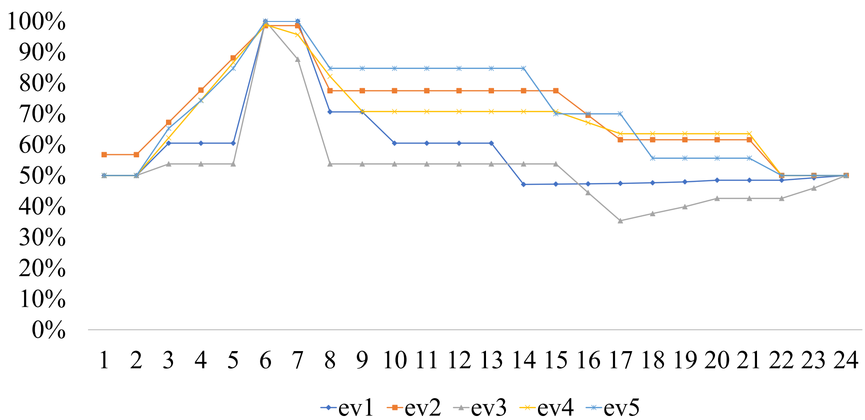

Figure 11
Aggregated state-of-charge levels of each EV type of the examined islanded power system

4.2 Energy Transition Case

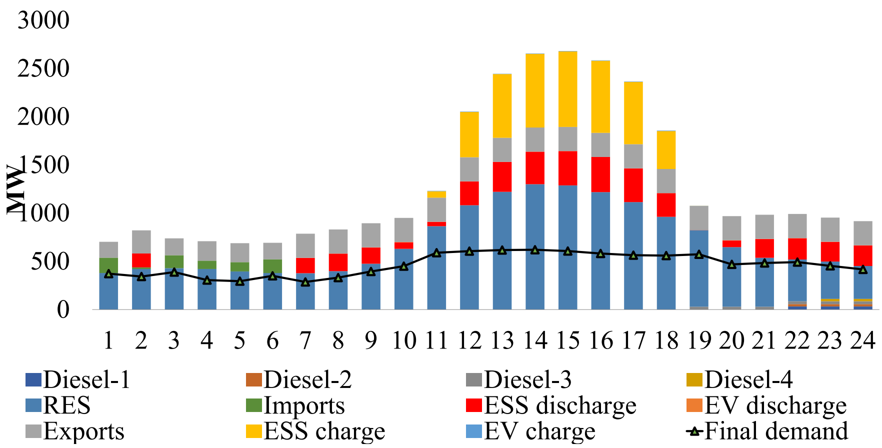

Figure 12

Hourly energy supply and demand mix of the examined islanded power system in the Energy Transition case

Figure 12 depicts the hourly energy supply and demand mix of the examined islanded power system in the Energy Transition case. This case is characterized by high penetration of RES in the power system. The results show that the islanded power system has been converted into a net electricity exporter, reporting around 5 GWh of net exports. Electricity imports occur only during the first 6 hours of the day when there is zero production from photovoltaics, and the diesel-fired power units are shut down. The aggregated electricity generation from diesel-fired power units has been minimized to less than 0.4 GWh daily, while ESS flexibility (charging and discharging cycle) is used during almost all of the hours of the day.

Figure 13 portrays the operating-up reserve provision mix of the examined islanded power system in the Energy Transition case. In contrast to the reference case where diesel-fired power units exclusively meet this service, there is a great diversification of that service's coverage in the Energy transition one. ESS contributes around 39% of the total daily needs, followed by the main grid with around 36%, the DRPs with almost 14%, diesel-fired power units with 9%, and EVs with less than 2%.

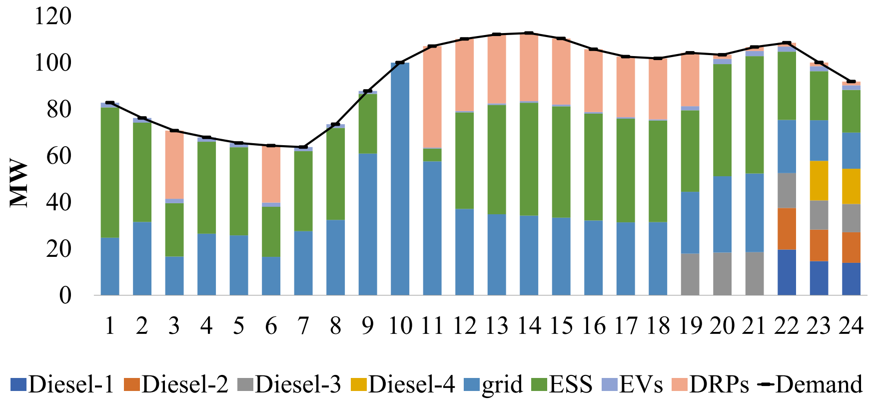

Figure 13
Operating-up reserve provision mix of the examined islanded power system in the Energy Transition case

Figure 14 portrays the operating-down reserve provision mix of the examined islanded power system in the Energy Transition case. All the available providers take part in the coverage of that service, with RES accounting for around 45%, ESS standing for 35%, DRPs with almost 13%, electricity interconnection with less than 5%, EVs with almost 2% and an almost negligible share from diesel-fired power units.

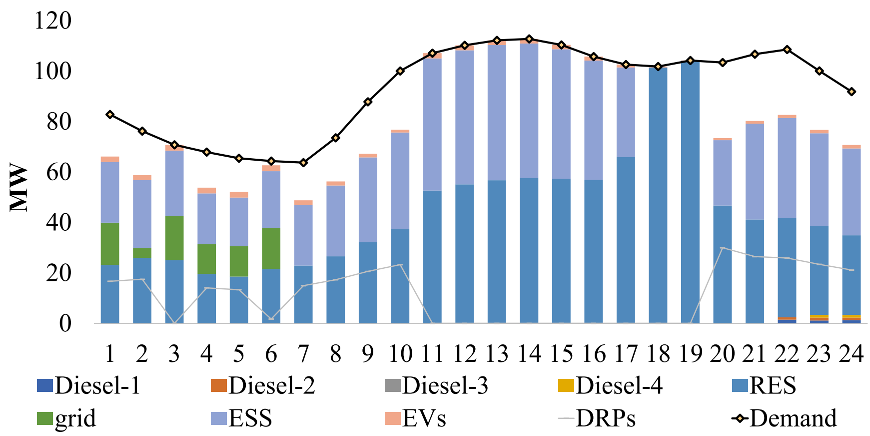

Figure 14
Operating-up reserve provision mix, for the examined islanded power system, in the Energy Transition case

Conclusions

In their efforts to meet their electricity needs in a dependable, cost-effective and long-term manner, islanded power systems face numerous obstacles. Taking into account the existence of various flexibility providers like ESS, EVs, and DRPs, this work proposes an optimization strategy, based on mixed-integer quadratic programming, to optimally determine an islanded power system's energy and reserves scheduling. It also examines the role that electricity interconnections play as providers of energy and reserve.

The results emphasize the significance of including these resources in the mix of energy and reserves, which may be even more significant, in the event of extremely high-RES penetration. In addition, the model outputs highlight the economic significance, when considering the electricity interconnection, with the mainland power system, compared to the case without.

All of these flexibility providers' design decisions and detailed testing of their performance on mid- and long-term planning frameworks, are future challenges.

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Appendix

Nomenclature

Sets

t	Time periods
i	Conventional power units (Diesel-fired power generators)
r	Renewable Energy Sources (RES)
v	Electric Vehicles (EVs)
w	Energy Storage Systems (ESSs)
y	Demand Response Programs (DRPs)
n	Upward reserve supplier resources (Conventional, ESSs, EVs, DRPs, Grid)
m	Downward reserve supplier resources (Conventional, ESSs, EVs, DRPs, Grid, RES)

Parameters

C_i^{stup}	Unit's i start-up cost
$C_{m,t}^{dn}$	Unit's m operating-down reserve provision cost
$C_{n,t}^{up}$	Unit's n operating-up reserve provision cost
$C_{r,t}^{curt}$	RES curtailment cost
DT_i	Unit's i minimum downtime
$D_{y,t}^{max}$	Maximum DRP consumption
$D_{y,t}^{min}$	Minimum DRP consumption
$D_{y,t}^{ref}$	DRP reference consumption level
EXP_t^{cap}	Maximum value of electricity exports
$E_{v,t}^{cons}$	EV energy consumption
$F_{r,t}$	RES availability factor
G_v^{ch-max}	EV maximum charging power
$G_v^{dis-max}$	EV maximum discharging power
G_w^{ch-max}	ESS maximum charging power
$G_w^{dis-max}$	ESS maximum discharging power
IMP_t^{cap}	Maximum value of electricity imports
P_i^{max}	Unit's i technical maximum
P_i^{min}	Unit's i technical minimum
RD_i	Unit's i ramp-down limit
RU_i	Unit's i ramp-up limit
R_t^{dn}	Operating-down reserve requirements
R_t^{up}	Operating-up reserve requirements
SF_v^{ch}	EV charging efficiency
SF_v^{dis}	EV discharging efficiency
SF_w^{ch}	ESS charging efficiency

SF_w^{dis}	ESS discharging efficiency
SOC_v^{max}	EV battery capacity
SOC_v^{min}	EV minimum allowable state-of-charge level
SOC_w^{max}	ESS maximum capacity
SOC_w^{min}	ESS minimum allowable state-of-charge level
UT_i	Unit's i minimum uptime
a_i, b_i, c_i	Production cost coefficients of unit i
n_v^{tot}	Number of EVs of each EV type

Variables

$c_{i,t}^{prod}$	Unit's i production cost in each time period t
$d_{y,t}^{cl}$	Cleared DRP energy consumption
imp_t	Electricity imports in each time period t
exp_t	Electricity exports in each time period t
$d_{y,t}^{dn}$	Downward DRP energy consumption
$d_{y,t}^{up}$	Upward DRP energy consumption
$p_{i,t}^{conv}$	Unit's i cleared total energy supply in each time period t
$p_{r,t}^{curt}$	Cleared amount of RES curtailed in each time period t
$p_{r,t}^{res}$	Cleared contribution of each RES directly utilized in each time period t
$p_{v,t}^{ch}$	Cleared EV charging power in each time period t
$p_{v,t}^{dis}$	Cleared EV discharging power in each time period t
$p_{w,t}^{ch}$	ESS cleared charging power in each time period t
$p_{w,t}^{dis}$	ESS cleared discharging power in each time period t
$r_{n,t}^{up}$	Unit's n cleared operating-up reserve supply
$r_{m,t}^{dn}$	Unit's m cleared operating-down reserve supply
r_t^{up}	Operating-up reserve supply from the mainland power system
r_t^{dn}	Operating-down reserve supply from the mainland power system
$soc_{v,t}^{ev}$	EV state-of-charge level
$soc_{w,t}^{st}$	ESS state-of-charge level

Binary variables

$y_{i,t}$	Unit's i start-up decision-making in each time period t
$z_{i,t}$	Unit's i shut-down decision-making in each time period t
$x_{i,t}^{oper}$	Unit's i operation decision-making in each time period t

Acronyms

DRPs	Demand Response Programs
ESSs	Energy Storage Systems
EVs	Electric Vehicles
RES	Renewable Energy Sources