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Economic assessment of smart grid initiatives for island power systems

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HIGHLIGHTS

- RES, ESS, DSM and EV initiatives for island power systems are economically assessed.
- Five representative prototype island power systems have been considered.
- Islands of different sizes and features require different initiatives.
- Multi-action initiatives mainly reduce system operation costs.
- Single-action initiatives mainly achieve best IRR.

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ABSTRACT

Islands are facing considerable challenges in meeting their energy needs in a sustainable, affordable and reliable way. The present paper develops an integrated approach to economically assess initiatives that can transform island power systems into smart ones. Single and multi-action initiatives fostering the deployment of renewable energy sources (RES), energy storage systems (ESS), demand-side management (DSM), and electric vehicle (EV) are considered. An hourly unit commitment on a weekly basis is proposed to assess the impact of the initiatives on the system operation costs of five prototype island power systems, which have been identified by applying clustering techniques to a set of sixty islands power systems. The different investment costs of the initiatives are accounted for determining their corresponding internal rate of return (IRR) through their lifetime. The economic assessment of single and multi-action initiatives for five prototype islands representing sixty island power systems quantifies which initiatives are most suitable for which type of island power system. The assessment shows that islands of different sizes and features require different initiatives. Larger islands tend to DSM initiatives, whereas smaller islands tend to RES initiatives. Multi-action initiatives achieve highest system operation cost reduction, whereas single action initiatives yield to highest IRR.

1. Introduction

Islands are facing considerable challenges in meeting their energy needs in a sustainable, affordable and reliable way. This is mainly due to the isolated nature and the small size of island power systems [1]. The geographic isolation also causes relatively high operation costs in comparison to large interconnected systems. Operation costs are not only higher because of expensive fuel transportation and lower efficiencies of the power generation technologies (e.g., Diesel), but also because of technical requirements on spinning reserves for guaranteeing frequency stability. Spinning reserve of island power systems usually covers the loss of the largest generating unit [2–5]. Actually, island power systems are more sensitive to frequency instability than larger interconnected systems since they exhibit a smaller inertia and each generating unit represents a significant fraction of the total generation infeed [6].

According to local resource availability, renewable energy sources (RES) offer an interesting solution to decrease the dependency on fossil fuels and increase island sustainability [7]. Since the intermittent behavior of RES can however affect the stability of island power systems, energy storage systems (ESS), electric vehicles (EV) offering a vehicle-to-grid operation, and demand-side management (DSM) have been introduced to mitigate the impact of the intermittent behavior of RES. In order to increase island sustainability, a combination of several actions needs therefore to be carried out, customized on specific islands, opportunities and constraints [8]. These actions that increase the flexibility of the system are allocated on the supply-side and the demand-side of

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Nomenclature

Sets

g	thermal unit
ess	energy storage system unit
h	hour
D	day
T	daily EV charging/discharging time window

Parameters

C_g^{fix}	the fixed cost of unit g [€]
C_g^{lin}	linear component of the variable cost of unit g [€/MW]
C_g^{qua}	quadratic component of the variable cost of unit g [€/MW^2]
$C_g^{start\text{-}up}$	start-up cost of generator g [€]
$C_g^{shut\text{-}down}$	shut-down cost of unit g [€]
$C^{rescurt}$	cost of RES curtailment [€/MW]
$P_g^{\min}$	minimum power generation of unit g [MW]
$P_g^{\max}$	maximum power generation of unit g [MW]
R_g^{up}	ramp-up of unit g [MW/h]
R_g^{down}	ramp-down of unit g [MW/h]
D_h	total power demand in hour h [MW]
$Pres_h$	wind and PV power production in hour h [MW]
$P_{ess,char}^{\max}$	maximum charging power of unit ess [MW]
$P_{ess,disch}^{\max}$	maximum discharging power of unit ess [MW]
$E_{ess}^{\min}$	minimum energy storage capacity of unit ess [MW h]
$E_{ess}^{\max}$	maximum energy storage capacity of unit ess [MW h]
η_{ess}^{char}	charging efficiency of unit ess
η_{ess}^{disch}	discharging efficiency of unit ess
$Ddisp^{max}$	maximum dispatchable power demand [MW]
$Ddisp^{min}$	minimum dispatchable power demand [MW]
$Ddispd_D^{\max}$	maximum dispatchable energy demand [MW h]
$Ddispd_D^{\min}$	minimum dispatchable energy demand [MW h]
$\delta Ddisp_h$	allocation of dispatchable demand $Ddisp$ in hour h
Dev^{max}	maximum charging/discharging EV power [MW]
$E_{eV}^{\min}$	minimum energy storage capacity of EVs, [MW h]
$E_{eV}^{\max}$	maximum energy storage capacity of EVs [MW h]
$Devd_D^{\max}$	maximum daily EV energy level [MW h]
$Devd_D^{\min}$	minimum daily EV energy level [MW h]
η_{eV}^{up}	charging efficiency of EV
η_{eV}^{down}	discharging efficiency of EV
δDev_h	allocation of EV charging/discharging in hour h

Binary decision variables

$\delta_{g,h}$	state of unit g in hour h
$\delta_{ess,disch,h}$	state of discharging of ess in hour h
$cx_{g,h}$	start-up decision of unit g in hour
$dx_{g,h}$	shut-down decision of unit g in hour h

Continuous decision variables

$p_{g,h}$	is the power generation of unit g in hour h [MW]
$prescurt_h$	curtailed RES generation in hour h [MW]
$resso_h^{up}$	system operator ramp-up spinning reserves required in hour h [MW]
$resso_h^{down}$	system operator ramp-down spinning reserves required in hour h [MW]
$resgen_h^{up}$	ramp-up spinning reserves provided by thermal generating units in hour h [MW]
$resgen_h^{down}$	ramp-down spinning reserves provided by thermal generating units in hour h [MW]
$resess_h^{up}$	effective ramp-up spinning reserves used from the energy storage systems in hour h [MW]
$resess_h^{down}$	effective ramp-down spinning reserves used from the energy storage systems in hour h [MW]
$pchar_{ess,h}$	charging power of unit ess in hour h [MW]
$pdisch_{ess,h}$	discharging power of unit ess in hour h [MW]
$e_{ess,h}$	is the actual energy storage capacity of unit ess in hour h [MW h]
$ddisp_h^{up}$	upward variation of the dispatchable component of the power demand in hour h
$ddisp_h^{down}$	downward variation of the dispatchable component of the power demand in hour h
dev_h^{up}	charging of EV in hour h
dev_h^{down}	discharging of EV in hour h
$resev_h^{up}$	effective ramp-up spinning reserves used from the EVs in hour h [MW]
$resev_h^{down}$	effective ramp-down spinning reserves used from the EVs in hour h [MW]
eev_h	is the actual energy storage capacity of unit ess in hour h [MW h]

the energy system [9,10]. Actions can be basically separated into three categories: (i) generation-side: use of natural gas and/or RES for power generation and use of ESS for reserve provision, (ii) grid-side: interconnection of island systems with other island systems or the continental system, and (iii) demand-side: use of ESS, implementation of DSM and promotion of EV. The use of natural gas instead of oil for power generation is however affected by the availability of local resources and/or the existence of economies of scale in both gas pipe lines and liquefied natural gas. Similarly, interconnection of an island system to the continent can be prevented by presence of deep waters and the existence of economies of scale (both in case of AC and HVDC transmission). Whereas past studies primarily focused on the optimal deployment of a single action, Ref. [11] has studied the impact of five different actions (DSM, use of natural gas, RES curtailment, ESS, and interconnectors) by combining some of them to improve RES integration and reduce system costs in the Western European system for 2050. ESS and interconnector options seem to be valuable for RES penetration above 60% of annual power generation.

The main objective of the present paper is to develop an integrated global approach to economically assess the main initiatives to be carried out over time that can transform island power systems into smart ones. This quantitative assessment is well suited to provide guidance on which initiatives are most suitable [11]. An initiative is understood as either a single action or a set of multiple actions. Different penetration levels of each action are considered. Since the shift from oil to gas and interconnection of islands to a continent can depend on local factors and on economies of scale, RES (particularly wind and PV generation), ESS, DSM, and EV actions are further investigated. Further, the multi-task capability of ESSs needs to considered as well. ESSs provide here both spinning reserve and load shifting services. Thus not only one type of action with different penetration levels but also multiple simultaneous actions and their impact on various islands of different features are economically assessed for the first time. The assessment consists of determining firstly the impact of single-action and multi-action initiatives on the system operation costs of an island power system. Furthermore, the different investment costs