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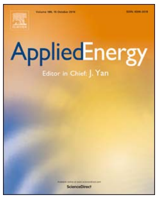

Techno-economic and business case assessment of multi-energy microgrids with co-optimization of energy, reserve and reliability services

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HIGHLIGHTS

- Microgrids provision of energy, reserve and reliability services is examined.
- Dynamic reliability price signals are formulated with a proposed stochastic approach.
- A MILP tool is proposed to co-optimise Microgrid behaviour when facing conflicting signals.
- Synergies and conflicts between price signals encourage different Microgrid behaviour.

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ABSTRACT

In this work a new techno-economic framework to model and assess business cases for energy, reserve and novel reliability services provided by Microgrids (MGs) is presented. The framework combines a bespoke Transactive Energy (TE) approach that aims at co-optimizing these potentially conflicting services. In this context, MGs aggregate, coordinate and exploit flexibility from emerging distributed energy resources and multiple energy vectors (e.g., electricity, heat and gas) as a means to partake in different services in response to price signals associated with markets and network needs. For example, MGs can provide reliability services to both the distribution network and their internal customers, owing to their ability to ride through contingencies by operating as islands. Further, MGs could coordinate with the network restoration scheme to reconnect to the network after a contingency occurs, and use their spare generation capacity to restore 'blocks' of other affected customers outside the MG. This novel application for MGs to improve network reliability has not yet been quantified from an economic perspective, especially in a TE context where conflicts with other services may arise. In this regard, it is clear that energy, reserve and reliability services may be economically attractive under specific conditions when assessed in isolation. However, their business case is still unclear in a pragmatic context where the provision of given services affects the economic operation of MGs, and may keep them from partaking in other services. On the above premises, this paper proposes a framework that combines a bespoke Mixed Integer Linear Programming (MILP) model for the operation of MGs, and a stochastic approach for simulating nonlinear and dynamic reliability price signals in light of MG reliability contributions assessed through Monte Carlo simulation. The framework is demonstrated on case studies based on pragmatic energy information, a real UK distribution network, sets of price signals for co-optimization of different services, and multi-energy MGs designed with Combined Heat and Power (CHP) units, Photovoltaic (PV) panels, Gas Boilers (GBs). Thermal Energy Storage (TES) and/or Battery Energy Storage (BES). The results demonstrate that, even though the operation schedule of devices within a MG can change based on the different technologies and price signals under consideration, the services are largely synergistic. This is a key finding, as it demonstrates that, for example, even without price signals from a reliability service the MG will have significant spare export capacity which, if accessible to the DNO, can improve the reliability of customers outside the MG.

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Nomenclature

Acronyms

BES	Battery Energy Storage
CHP	Combined Heat and Power
CI	Customer Interruptions
CML	Customer Minutes Lost
DE	dynamic energy
DNO	Distribution Network Operator
GB	Gas Boiler
MILP	Mixed Integer Linear Programming
MG	Microgrid
NOP	Normally Open Point
PV	Photovoltaic
RE	retail energy
Rel	reliability
Res	reserve
STOR	short term operating reserve
TES	Thermal Energy Storage

Indices

b	index of buildings, 1 toN_b
g	index of reliability price buckets, 1 to N_g
i	index of settlement periods, 1 to N_i
s	index of scenarios, 1 to N_s

Parameters

M	arbitrarily large number

Resource

B^{min}/B^{max}	BES energy min/max (kWh$_e$)
Cx	TES thermal capacitance (kWh$_{th}$/K)
H^{CHPmin}/H^{CHPmax}	CHP min/max heating power (kW$_{th}$)
H^{GBmin}/H^{GBmax}	GB min/max heating power (kW$_{th}$)
P^{BESmin}/P^{BESmax}	BES power (min/max) (kW$_e$)
Rx	TES thermal resistance (kWh$_{th}$/K)
$T_{s,i}$	environmental temperature (K)
X^{min}/X^{max}	TES energy min/max (K)
η^{GB}	GB efficiency (–)
	CHP thermal/electrical efficiency (–)
φ	BES round-trip efficiency (–)

Demand/generation

$E_{s,i,b}^{load}$	electricity load (kWh$_e$)
$E_{s,i,b}^{solar}$	solar electricity generation (kWh$_e$)
$H_{s,i,b}^{del}$	heat load (kWh$_{th}$)

Price profiles and parameters

$\lambda_{s,i}^{-}/\lambda_{s,i}^{+}$	market electricity import/export price (£/kWh$_e$)
$\gamma_{s,i}$	gas price (£/kWh$_{gas}$)
$\pi_{s,i}$	reserve availability price (£/kW$_e$/h)
$\beta_{s,i}$	reliability service price (£/kW$_e$/h)
ϕ	reliability service indicator (binary)
$Rcall$	max length of reserve call (h)
$Relcall$	max length of reliability event (h)
ω_i	reserve window indicator (binary)

Time-band length

t	length of time step (h)

Variables: Resource

$B_{s,i}$	battery energy (kWh$_e$)
$G_{s,i}^{GB}$	GB gas consumption (kW$_{gas}$)
$G(m)_{s,i}$	MG gas consumption (kW$_{gas}$)
$P_{s,i}^{BES+}/P_{s,i}^{BES-}$	battery export/import power (kW$_e$)
$P_{s,i}^{CHP}$	CHP electrical power (kW$_e$)
$X_{s,i}$	TES energy (kWh$_{th}$)
$x_{s,i,g}/y_{s,i}/z_{s,i}$	binary variables (binary)

Variables: Energy, reserve and reliability services

$R_{s,i}^{BES}$	BES reserve (kW$_e$)
$R_{s,i}^{CHP}$	CHP reserve (kW$_e$)
$Rel_{s,i}^{BES}$	BES reliability service capacity (kW$_e$)
$Rel_{s,i}^{CHP}$	CHP reliability service capacity (kW$_e$)
$R(m)_s$	MG reserve (kW$_e$)
$Rel(m)_{s,i}$	MG reliability service capacity (kW$_e$)
$Rel(m)_{s,i}^{D}$	MG reliability service capacity dummy variable (kW$_e$)
$Rel(m)_{s,i,g}^{G}$	MG reliability service bucket capacity (kW$_e$)
$M_{s,i}^{-}/M_{s,i}^{+}$	market energy import/export (kWh$_e$)

1. Introduction

The energy system is facing new and significant challenges and opportunities due to the large scale integration of distributed energy resources, such as solar Photovoltaic (PV) panels, Combined Heat and Power (CHP) units, Battery Energy Storage (BES), Thermal Energy Storage (TES), for instance at the level of neighbourhoods and communities [1,2]. In particular, new opportunities to improve energy system performance arise due to the potential of distributed energy resources to facilitate meeting existing and future energy needs in an economic, reliable, environmental and socially acceptable manner [3].

However, the effective use of these distributed resources, which are effectively small, aggregated multi-energy systems [4], is a grand challenge that requires the development of novel concepts. One of these is grid-connected Microgrids (MGs), whereby distributed energy resources are aggregated, coordinated and optimized so as to exploit their inherent flexibility and facilitate interaction with the upstream grid. These resources can then be used to assist effective operation of the energy system. To enable MGs, it is vital to understand and quantify from the technical and economic perspectives their potential to provide specific services to the energy system. For example, MGs can provide traditional energy and reserve services, as well as novel *reliability services* that exploit specific features of MGs (this is briefly mentioned below and discussed in detail in Section 2.1). These services may be economically attractive for MGs when provided independently and only considering the relevant price signal. However, it is unclear if the MG would be incentivised to partake in multiple services simultaneously due to potential conflicts and synergies between price signals that may change depending on the nature of the MG.

1.1. Literature survey

The potential of distributed multi-energy systems, such as MGs, to use their inherent flexibility for a wide range of services for the energy sector is well recognised. However, most available tools for the assessment of relevant business cases are generally only suitable for single technologies, such as PV panels, as considered by Matualitis et al. [5], or CHP units, as considered by Merkel et al. [6]. This disregards the