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A multi-objective framework for cost-unavailability optimisation of residential distributed energy system design

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ABSTRACT

Future energy systems are expected to include distributed energy systems (DES) and microgrids (MG) at the distribution level. These energy efficient environments enable participating consumers to locally generate and share both electrical and thermal energy. Apart from the potential for a more cost-efficient energy system design, improved system availability is also increasingly put forward as a major advantage of MGs. This paper proposes a mixed-integer linear programming (MILP) approach for the design of a neighbourhood-based energy system, considering the trade-off between total annualised cost and electrical system unavailability. System design is optimised to meet the yearly neighbourhood energy demands by selecting technologies and interactions from a pool of dispatchable and renewable poly-generation and storage alternatives. The availability implementation employs a Markov chain approach combined with logic-gate integer programming. The Pareto trade-off sets of on- and off-grid MG modes are obtained using a weighted-sum approach. The developed model is subsequently applied to an Australian case-study. The sought after trade-off "knee" points for each Pareto curve are hereby identified. Additionally, through comparing on- and off-grid design trade-offs, the need for component redundancy for systems with islanding capabilities is analysed.

1. Introduction

1.1. Background

Residential distributed energy systems (DES) are gaining increasing interest as a solution for challenges affecting traditional top-down energy systems [1–3]. Conventionally, electricity is generated in large centralised power plants to be transmitted and distributed to consumers in the grid [2,3]. This conventional system faces challenges with regard to growing global energy needs, emissions and the need for alternative energy resources [4]. DES have the potential to increase system efficiency and reduce emissions through strategic energy-integrated design. Residential DES refer to a residential area that has the option to install distributed generation units (DG), storage units and local energy sharing of heating, cooling and electricity [5,6]. DG units refer to small-scale units located close to end-consumers at the distribution level in the grid [5,6]. A small system where energy can be locally generated through DG units and shared among participants organised through a central control unit is defined as a microgrid (MG) – if predominantly electricity based –, or, a DES more generally. MGs introduce various potential benefits to end-consumers of which increased electrical system dependability is often highlighted [1,7,8].

In order for MGs to emerge on a wide-spread scale, a cost effective, efficient and dependable energy system design is required. This paper presents a generic optimisation-based decision-making approach to assess the relative benefit in terms of cost and electrical system availability of a small residential energy system. This trade-off is especially interesting in MG systems since local energy generation and integration can offer increased electrical availability within low voltage distribution systems that are responsible for over 90% of end-consumer interruptions [9].

1.2. Availability as an attribute of dependability

Distributed energy resource planning problems are inherently multi-objective (MO) since they involve many stakeholder interests, often conflicting, that need to be considered and traded off [10]. Apart from system cost, system dependability is of major

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Nomenclature

Abbreviations

A	Availability
AC	Absorption chiller
$C^{\mathrm{LOAD}}_{\mathrm{ELEC}}$	Electricity load [kW]
C	Cold storage tank
CHP	Combined heat and power unit
D/dump	Dump load
DES	Distributed energy system
DG	Distributed generation unit
ELEC/E	Electricity
EST	Electrical storage unit
GRID/GR	Central electricity supply
h	House
H	Hot storage tank
HEAT/H	Heating
LDC	Load duration curve
MG	Microgrid
MGCC	Microgrid central control unit
MILP	Mixed-integer linear programming
MO	Multi-objective
OM	Operation and maintenance
PV	Photovoltaic unit
SAIDI	System Average Interruption Duration Index
U/UA	Unavailability

Parameters

A^{com}_{tech}	Component availability of technology *tech* [%]
A^{res}_{tech}	Resource availability of technology *tech* [%]
A^{sup}_{tech}	Supply availability of technology *tech* [%]
a_{tech}	Availability of technology *tech* [%]
L_{tech}	Lower bound on installed capacity of technology *tech* [kW or kWh]
n_h	Number of houses in the neighbourhood
P_s	Probability of a system being in state *s* [%]
$T^{av}_{tech,i}$	Threshold capacity for 100% availability of technology *tech* in house *i* [m^2 or kWh]
$T^{av}_{CHPmg,i}$	Threshold capacity for 100% MG-availability of technology *tech* to house *i* [m^2 or kWh]
U_{tech}	Upper bound on installed capacity of technology *tech* [kW or kWh]
ua_{con}	Unavailability of household electrical system configuration con
ua_{tech}	Unavailability of technology *tech* [%]
UA^{com}_{tech}	Component unavailability of technology *tech* [%]
UA^{res}_{tech}	Resource unavailability of technology *tech* [%]
UA^{sup}_{tech}	Supply unavailability of technology *tech* [%]
UA^{tot}_{tech}	Total unavailability of technology *tech* [%]
λ_c	Unity weighting factor
μ	Constant component repair rate
ϕ	Constant component failure rate

Variables

$B_{con,i}$	Binary variable that decides on the installation of an electrical system configuration *con* in house *i*
$B_{tech,i}$	Binary variable that decides on the installation of (unavailable) technology *tech* in house *i*
$B^{av}_{MG,tech,i}$	Binary variable that decides on the installation of MG-available technology *tech* in house *i*
$B^{av}_{tech,i}$	Binary variable that decides on the installation of available technology *tech* in house *i*
C^{CT}_i	Annualised carbon tax cost of houses *i* [AUD y^{-1}]
$C^{FUEL}_{i,tech}$	Annualised fuel cost of technologies *tech* in houses *i* [AUD y^{-1}]
$C^{GRID}_{BUY,i}$	Annualised grid electricity import cost of houses *i* [AUD y^{-1}]
$C^{GRID}_{SELL,i}$	Annualised grid electricity export income of houses *i* [AUD y^{-1}]
$C^{INV}_{i,tech}$	Annualised investment cost of technologies *tech* in houses *i* [AUD y^{-1}]
$C^{OM}_{i,tech}$	Annualised OM cost of technologies *tech* in houses *i* [AUD y^{-1}]
C^{TOT}	Total annualised cost [AUD y^{-1}]
$C^{TOT,S}$	Scaled total annualised cost [kAUD y^{-1}]
CHP^A_i	Binary variable that decides on the implementation of CHP capacity level in house *i*
CHP^B_i	Binary variable that decides on the implementation of CHP capacity level in house *i*
CHP^C_i	Binary variable that decides on the implementation of CHP capacity level in house *i*
$DG^{MAX}_{tech,i}$	Total installed capacity of technology *tech* in house *i* [kW or kWh]
GC_i	Binary variable that decides on the implementation of grid connection to house *i*
$MGA_{i,k}$	Binary variable that decides on the implementation of an available MG with *k* MG-available CHP units to house *i*
UA_i	Electrical system unavailability of house *i* [nines]
$UA^{TOT,S}$	Scaled average household electrical system unavailability [nines]
XC_i	Binary variable that decides on the implementation of a household-available CHP and grid connection for house *i*

importance in DES. A dependable system allows trusting the services it is supposed to deliver [11]. An analysis of the dependability of a system entails the research of a wide range of aspects [11–19]. The two most employed attributes to measure system dependability are availability and reliability, which serve different purposes highlighted by their definitions [11–19];

Availability is the probability that a system is employable at a certain time *t*, i.e. the readiness for correct service. Availability measures the dependability of repairable systems. Unavailability is its complement.

Reliability is the probability that a system works correctly over a certain time interval Δt, provided it worked correctly at the start of this interval. Reliability is mostly employed for irreparable or continuously operating systems. The complement of reliability is unreliability.

Availability is chosen as measure since residential DES are: (i) non-critical in operation in contrast with, e.g. continuous critical processes [20], (ii) readily maintainable and repairable within reasonable time frames [21], and (iii) expected to work at a certain time *t*, i.e. consumers expect the light to go on when flicking a switch. Availability refers here to the probability of a unit to provide (full) power to the load at any time *t* [21].

1.3. Determining availability

Electrical system availability is typically expressed through so-called "nines" [22]. Central grid availability, for example, can range