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Robust economic optimization and environmental policy analysis for microgrid planning: An application to Taichung Industrial Park, Taiwan

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ABSTRACT

This study aims to provide economical and environmentally friendly solutions for a microgrid system with distributed energy resources in the design stage, considering multiple uncertainties during operation and conflicting interests among diverse microgrid stakeholders. For the purpose, we develop a multi-objective optimization model for robust microgrid planning, on the basis of an economic robustness measure, i.e. the worst-case cost among possible scenarios, to reduce the variability among scenario costs caused by uncertainties. The efficacy of the model is successfully demonstrated by applying it to Taichung Industrial Park in Taiwan, an industrial complex, where significant amount of greenhouse gases are emitted. Our findings show that the most robust solution, but the highest cost, mainly includes 45% (26.8 MW) of gas engine and 47% (28 MW) of photovoltaic panel with the highest system capacity (59 MW). Further analyses reveal the environmental benefits from the significant reduction of the expected annual CO_2 emission and carbon tax by about half of the current utility facilities in the region. In conclusion, the developed model provides an efficient decision-making tool for robust microgrid planning at the preliminary stage.

1. Introduction

Climate change is one of the most serious global issues that we are facing. According to Central Weather Bureau (CWB), Taiwan has seen its temperature gone up by 1.4°C [1]. Among many factors, the electricity sector is a major source of greenhouse gas (GHG) emissions that contribute to climate change [2]. Switching a substantial portion of electricity generating capacity away from fossil fuels to renewable energy technologies could have a significant effect in reducing GHG. In addition, the increasing frequency of natural disasters put forward the flexibility and independence of electricity generation from the central generation. In this context, a “microgrid”, is considered as one of the most promising options to provide a more secure, clean, and efficient energy supply. The microgrid is a local generation of heat and electricity which combines distributed energy resources (DERs) in which most of them are renewable energy resources with distributed energy storages (DESs).

There have been many researches on microgrid regarding autonomous operations [3–5], control schemes [5–9], scheduling [10–17] and planning [3,18–22]. However, robust optimization of microgrid planning has not been studied yet despite its importance. Since microgrid itself has lots of uncertainties including demand variation, fuel price fluctuation, regulation change, etc., it is practically important to study and develop robust optimization strategies that take these uncertainties into account at the planning stage. Furthermore, diverse stakeholders could participate in microgrid development and management, including microgrid

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Nomenclature (variables: lower case letters; parameters: upper-case and greek letters)

A	a large number
allot	allocated electrical energy for DER, kWh
apv	area of the solar panels, m^2
c	overall cost, $
cap	capacity of DER, kW
caps	capacity of DES, kWh
cbuyn	cost of purchasing electricity, $
cctax	cost of carbon tax, $
cfuel	cost of fuel, $
cinv	cost of capital investment, $
CLIM	allowable carbon emission, kg
com	cost of operation and maintenance, $
CTAX	unit carbon tax on the excess carbon emission, $
DCI	carbon intensity of the DER power, kg/kWh
disc	energy discharged from DES, kWh
dm	excess carbon emission, kg
ebuyn	power from utility grid, kWh
ECI	carbon intensity of the utility power, kg/kWh
eder	power supply from DER, kWh
EL	power load capacity, kW
EP	unit power tariff, $/kWh
esal	sold power to the utility grid, kWh
f	objective cost, $
fboi	fuel consumption for boiler, kg
FC	fixed unit capital cost, $/kW
FCI	carbon intensity of the fuel, kg/kg
FCNV	fuel to power conversion rate, kWh/kg
FCS	unit capital cost for DES, $/kWh
fder	fuel consumption for DER, kg
FP	unit fuel charge, $/kg
hboi	heat generated from boiler, kWh
hder	heat generated by DER and directly utilized, kWh
HL	heat load capacity, kW
Ir	interest rate
L	weight of the expected cost
lose	total expended energy from the DES, kWh
LT	lifetime of the DER, year
MAXE	maximum capacity of the DER, kW
MAXS	capacity upper bound of DES, kWh
MINS	Minimum discharged power, kWh
N	minimum types of DER
OMF	fixed cost on operation and maintenance, $/kW
OMV	variable cost on operation and maintenance, $/kWh
QT	lifetime of the DES, year
rsal	revenue from selling electricity, $/kWh
save	stored energy, kWh
SP	unit power feed in tariff, $/kWh
store	DES storage level, kWh
T	hour in a month
u	cost, $
VC	cut-in wind speed, m/s
VF	cut-off wind speed, m/s
VN	nominal wind speed, m/s
VW	monthly average wind speed, m/s
y	equal to 1 when the DER is selected, otherwise 0
ybuy	equal to 1 when buy from utility grid, otherwise 0
ydisc	equal to 1 when discharge from DES, otherwise 0
ysal	equal to 1 when sell power to utility grid, otherwise 0
ysave	equal to 1 when store energy from DES, otherwise 0

Greek symbols

α	heat recovery rate of DER
β	heat efficiency in the boiler
δ	DER efficiency
ε	storage round trip efficiency
ζ	storage coefficient
η	minimum share of power generation from the DER
θ	energy efficiency of PV
λ	lower bound of energy share
φ	lower bound of the energy demand that should be satisfied by the microgrid

Subscripts

batt	battery storage
f	index of fuel
i	index of DER technology
E	Expected
m	index of month
PV	photovoltaic panel
q	index of storage type, power or heat
s	index of scenario
thermo	thermo storage
WC	worst case
WT	wind turbine

developers, microgrid operators, and/or civil society. Some of their objectives are often naturally conflicting, indicating that there is no single solution that meets all stakeholders. For example, civil society's interest in reducing CO_2 emission conflicts with the need for an affordable and reliable energy supply. Thus, it is required to obtain a set of compromised solutions in microgrid planning among the conflicting objectives, called a Pareto solution set [23]. To this end, this study develops a robust optimization model to determine the capacity of DERs and DESs considering multiple objectives.

"Robustness" herein is referred to as the risk aversion, which could be considered differently depending on the nature of variables. Generally, these variables can be categorized into three types [24,25]: (i) scenario-independent variables (e.g. capacity of equipment), (ii) scenario-dependent technical variables (e.g., current, voltage, and frequency), and (iii) scenario-dependent economic variables (e.g., cost, profit). In the case of scenario-dependent economic variables, the robustness (i.e., *economic robustness*) concept should focus on reducing the comparatively high scenario costs, while keeping the overall average cost as low as possible. On the other hand, the robustness measuring the scenario-dependent technical variables (i.e. *technical robustness*) should be considered on the basis that the operating conditions must be insensitive to variations within certain ranges as defined by the scenarios. Accordingly, economic robustness adopts a monotonic function while the function of technical robustness is symmetric [22,25]. It should be noted that Pareto optimality, one of the important criteria for multi-objective optimization, is guaranteed only for monotonic robustness measures [22,25]. Thus, the current study particularly considers the economic robustness in microgrid planning in order to guarantee Pareto Optimality with monotonic economic robustness measures.