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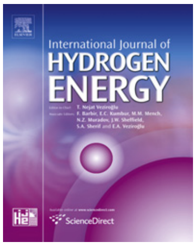

Fuel cell micro-CHP techno-economics: Part 1 – model concept and formulation

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ARTICLE INFO

Article history:
Received 27 May 2009
Received in revised form
18 September 2009
Accepted 26 September 2009
Available online 24 October 2009

Keywords:
Micro-CHP
Cogeneration
Unit commitment
Mixed integer
Degradation

ABSTRACT

This article presents the concept and mathematical treatment for a techno-economic modelling framework designed to enable exploration of fuel cell micro combined heat and power (micro-CHP) system design and control. The aim is to provide a tool that can help to focus research and development attention on the system characteristics critical for commercial success of these technologies, present cost targets for developers, and to ensure policy makers provide appropriate instruments to support commercialisation. The model is distinctive in that it applies mixed integer unit commitment formulation to link design and control decisions for micro-CHP, and explicitly characterises stack degradation in a techno-economic framework. It is structured to provide depiction of the fuel cell stack and balance-of-plant, supplementary thermal-only system (e.g. tail gas burner), thermal energy storage, and electrical power storage. Technically, the fuel cell stack is characterised by steady-state thermal and electrical efficiencies for full and part-load operation, its nameplate capacity, minimum operating set-point, and stack degradation via performance loss rate proportional to power density and thermal cycling rate. The dynamics of operation are emulated via ramp limits, minimum up-time and minimum down-time constraints, and start-up and shutdown costs and energy consumptions. The primary performance evaluation metric adopted is the maximum additional capital cost a rational investor would pay for the fuel cell micro-CHP system over and above what they would pay for a competing conventional heating system. The companion article (Part 2) applies the developed model to consider the impact of stack degradation on economic and environmental performance.

1. Introduction

Fuel cell based micro combined heat and power (micro-CHP) is a promising technology to efficiently meet heating and some electricity needs of residential dwellings. It has the potential to reduce carbon dioxide emissions related to energy consumption in the domestic sector, can reduce primary energy consumption which could improve national energy security, and could be a cost-effective means of meeting residential energy needs if capital cost targets can be met. Furthermore, potential market size is large, suggesting the technologies could be become important in overall energy supply [1–3]. As fuel cells are an emerging technology, it is timely to provide developers and policy makers with

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doi:10.1016/j.ijhydene.2009.09.094

Nomenclature

Objective

Lifetime Cost	The operation and maintenance cost of meeting energy demand over the fuel cell's lifetime.

Decision Variables

$a_{2,t},\ldots,a_{L,t}$	Piecewise electrical output (kW $_e$h) of micro-CHP in time period t.
$\alpha_{1,t},\ldots,\alpha_{L,t}$	State of each segment of piecewise electrical output – 0 = not fully dispatched, 1 = fully dispatched for each time period t.
$S_{st,t}$	Start-up cost for fuel cell stack in time period t.
$S_{sd,t}$	Shutdown cost for micro-CHP in time period t.
b	Thermal output (kW $_{th}$h) of supplementary heat-only unit in time period t.
c_t	Electricity bought (kW $_e$h) from the grid in time period t.
d_t	Electricity sold (kW $_e$h) to the grid in time period t.
e_t	Electricity used to charge electricity storage (kW $_e$h) in time period t.
f_t	Electricity discharged from electricity storage (kW $_e$h) in time period t.
g_t	Thermal energy charge to thermal storage (kW $_{th}$h) in time period t.
h_t	Thermal energy discharged from thermal storage (kW $_{th}$h) in time period t.

Constants

λ_{FC}	Lifetime of the fuel cell stack in years.
FC_{cap}	Nameplate capacity of fuel cell stack (kW_e).
B_{cap}	Nameplate capacity of supplementary heat-only unit (kW_{th})
ES_{cap}	Nameplate capacity of electricity storage unit (kW_eh)
TES_{cap}	Nameplate capacity of thermal energy storage unit (kW_{th}h)
ζ	Binary variable indicating if a micro-CHP is present.
ϑ	Binary variable indicating if electricity storage is present.
μ	Binary variable indicating if thermal energy storage is present.
$D_1,\ldots,D_L$	Breakpoints in micro-CHP piecewise linear generating cost function
$\eta_{FC,1},\ldots,\eta_{FC,L}$	Initial fuel cell net LHV electrical efficiency coefficients.
$\sigma_{FC,1},\ldots,\sigma_{FC,L}$	Fuel cell net LHV overall efficiency (heat + power) coefficients.
τ_d	Minimum down-time of fuel cell stack (no. of time periods).
τ_u	Minimum up-time of fuel cell stack (no. of time periods).
τ_s	Number of time periods in fuel cell start-up cost function.
$s_{start,\tau}$	Start-up cost of micro-CHP system if started after τ time periods off (£).
$s_{shutdown}$	Shutdown cost of micro-CHP system (£).
r_{up}	Maximum ramp up for micro-CHP (kW $_e$ per time period).
r_{down}	Maximum ramp down for micro-CHP (kW $_e$ per time period).
κ_η	Micro-CHP electrical efficiency degradation coefficient (%/kW $_e$h/$kW_{installed}$).
φ_η	Micro-CHP electrical efficiency degradation coefficient (%/thermal cycle)
σ_{SHU}	Supplementary heat-only unit LHV efficiency.
u_{ch}	Electricity storage unit maximum charge rate (kW $_e$h per time period).
u_{dis}	Electricity storage unit maximum discharge rate (kW $_e$h per time period).
υ_{ch}	Thermal energy storage unit maximum charge rate (kW $_{th}$h per time period).
υ_{dis}	Thermal energy storage unit maximum discharge rate (kW $_{th}$h per time period).
η_{ch-es}	Electricity storage charge efficiency.
η_{dis-es}	Electricity storage discharge efficiency.
η_{ch-tes}	Thermal energy storage charge efficiency.
$\eta_{dis-tes}$	Thermal energy storage charge efficiency.
m_{FC}	Fuel cell stack maintenance cost per year (£/year).
m_{SHU}	Supplementary heat-only unit maintenance cost (£/year).
m_{ES}	Electricity storage maintenance cost (£/year).
m_{TES}	Thermal energy storage maintenance cost (£/year).
ϵ_t	Electricity price from grid (£/kWh) in time period t.
γ_t	Gas price (£/kWh) in time period t.
β_t	Electricity buyback price (£/kWh) in time period t.
AM	Combined lifetime maintenance costs for all equipment (£).
OP	Combined lifetime fuel and electricity cost minus revenue (£)
ω_z	Weighting for day-types in the problem, for each day-type z.
$EDem_t$	Electricity demand in time period t
$HDem_t$	Heat demand in time period t
T	Number of time periods in one sample day.
L	Number of piecewise linear elements for fuel cell electricity production cost function.
Z	Number of representative sample days analysed in the problem.

information regarding their economic and environmental sensitivities and potential, and the relative importance of each of their technical constraints. This can aid developers in focusing research and development attention, and policy makers in formulating relevant and effective instruments to support commercialisation for the sector. A building block of most such analyses is techno-economic modelling of the systems.

This article presents the concept and develops a mathematical formulation for a techno-economic model designed to