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A multi-period Mixed Integer Linear Program for design of residential distributed energy centres with thermal demand data discretisation

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ABSTRACT

Distributed Energy (DE) has gained significant interest in recent years as a way to maximise the efficient use of fuel for the production of electricity and heat. The concept of DE is to produce energy close to the end users. The increased fuel efficiency allows a significant reduction in carbon dioxide (CO_2) emissions. In this paper, the sizes and the number of heat and power supply units are determined by an optimisation procedure that minimises the total annual cost. A Mixed Integer Linear Programming (MILP) model is developed to design new DE centres from a portfolio of possible technologies to service the thermal and power demand profiles of a geographic region. In this model, the partial load required for the combined heat and power (CHP) units and the equipment operating schedule in time intervals are selected to meet the demand data. The approach requires that energy demand be represented by discrete time bands to model the variations according to the time of day, day of the week and season of the year. Selection of inappropriate time bands can lead to misleading results. In this paper a systematic procedure for selecting time bands is proposed. The optimisation model is demonstrated in a case study. Results indicate that 70%–86% reduction in CO_2 emissions is possible relative to individual building heating systems. Including thermal storage in the design of distributed energy centres achieves 54% reduction in CO_2 emissions compared to design without thermal storage, since fossil fuelled units are not operated continuously.

Keywords: Distributed energy (DE); Time band selection; Operating schedule; Part load; Mixed Integer Linear Programming (MILP)

1. Introduction

Climate change has promoted the setting of binding targets for industrialised countries to reduce greenhouse gas (GHG) emissions. As an example, the UK must realise at least an 80% cut in greenhouse gas emissions by 2050 and at least 34% by 2020 against a 1990 baseline (Department of Energy and Climate Change, 2008). In order to meet these targets there must not only be a substantive reduction in energy consumption, but also a significant change in the approach to energy production.

Conventionally, in the UK, electricity is produced in centralised power stations with a typical efficiency based on fuel value between, 35% and 45%. Even though power generation in combined cycle plants can in principle achieve a higher efficiency of the order of 60%, still lower efficiencies are typical. Domestically and commercially, heat is mostly produced locally by stand-alone boilers with efficiencies between 80% and 90%. In addition, electricity produced in central power generation has an efficiency distribution loss of between 5% and 7% of the electricity fed into the grid. This implies that the energy generation efficiency for satisfying

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Nomenclature

Independent variables

PL	Part-load, %
P_{in}	Electrical power input to the system, MW
P_{out}	Electrical power output of the system, MW
$Q_{TS\,max}$	Thermal storage tank capacity, MWh
Q_{TSin}	Heat flow diverted to thermal storage unit, MW
Q_{TSout}	Heat flow extracted from thermal storage unit, MW
y_e	Binary variable for existence of supply units
y_p	Binary variable for power being bought or sold
y_w	Binary variable for 'on'/'off' operational mode
y_{TS}	Binary variable for thermal storage being charged or discharged

Dependent variables

C_{Fuel}	Total annual cost of fuel, £/yr
$C_{Maint.}$	Total annual maintenance cost, £/yr
$C_{Opera.}$	Total annualised operating costs, £/yr
C_{Power}	Net annual cost of power (positive when power is imported and negative when power is exported), £/yr
C_{Total}	Total annualised costs, £/yr
$C_{Tcapital}$	Annualised total capital costs, £/yr
CO_2	Mass flow rate of CO_2 emissions (t/yr)
F	Fuel consumption in volume per hour, N m^3/h or L/h
P	Power output of a supply unit, MW
Q	Thermal output of a supply unit, MW
Q_{TS}	Heat stored in the thermal storage tank, MWh

Parameters

a	Slope of the linear fuel consumption function of supply units
Af	Annualisation factor, yr^{-1}
b	Independent term of the linear fuel consumption function of supply units, N m^3/h or L/h
BD	Based load thermal demand, MW
c	Slope of the linear power output function, MW
C_{capex}	Cost of purchase and installation, £/MW (£/m^3 for thermal storage unit)
c_f	Fuel price per unit volume, £/m^3 or £/L
c_{mf}	Fixed annual maintenance cost, £/yr
c_{mv}	Variable maintenance cost, £/MWh
$c_{Pbought}$	Purchase price for electrical power, £/MWh
c_{Psold}	Sales tariff for electrical power, £/MWh
d	Independent term of the linear power output function of supply units, MW
e_f	CO_2 emissions in manufacture of a supply unit, $kgCO_2$/MWh
e_v	CO_2 emission rate per type of fuel burnt, $kgCO_2$/N m^3 or $kgCO_2$/L
e_p	Grid CO_2 emission factor, $kgCO_2$/kWh
IF	Fraction of heat stored with respect to thermal storage tank capacity at start of accumulation period
Lf	Losses factor of thermal storage, e.g. 2% in a day
P_D	Electrical power demand, MW
PD	Peak thermal demand, MW
PL_{max}	Maximum part-load of a 'unit type' (e.g. 100%)
PL_{min}	Minimum part-load of a 'unit type' (e.g. 50%)
P_T	Power output at 100% capacity, MW
Q_D	Thermal demand, MW
Q_T	Thermal output at 100% capacity, MW
$ratio_{CHPe}$	Power to heat ratio
T	Hours in a time band, h
TAQ_D	Total annual thermal demand, MW

Subscripts

i	Supply unit
j	Hourly thermal demand, MW
n	Total number of hours in a year
p	Time band

domestic demand for heat based on stand-alone boilers, and power based on centralised power stations is 40%–50%.

Distributed Energy (DE) is an alternative approach that refers to the local generation of heat and electricity mainly through combined heat and power (CHP) systems or renewable energy conversion devices (Pepermans et al., 2005). Combined local production of heat and power has the advantage of a high efficiency, and enable the use of thermal energy that would otherwise be wasted in centralised systems (Manfren et al., 2011). Electricity is fed to a grid that might be local or national, and heat in the form of hot water or steam is distributed through a District Heating Network (DHN) (Manfren et al., 2011). The energy generation efficiency of DE could be as high as 85% to 90%, leading to a significant potential to improve overall fuel efficiency and reduce CO_2 emissions. Distributed energy centres are a good option for future residential energy systems with respect to sustainable development (Ren and Gao, 2010).

Although DE offers such a great advantage and has been applied to some extent and with success in countries such as Denmark (Van der Vleuten and Raven, 2006) and Sweden (Holmgren, 2006), there is no systematic methodology to design new DE centres, especially when a wide range of technology options are considered (Ren and Gao, 2010). Such methodology should allow the selection of supply units, their size, and operating schedule. Part load operation needs also to be considered in the design, and optimal operation for the best plant performance in terms of capital cost, operating costs and CO_2 emissions. The methodological framework should also allow for inclusion of thermal storage, so that fossil fuelled units are not operated continuously (Haeseldonckx et al., 2007). There is limited use of thermal storage and cogeneration in existing district heating schemes (Holmgren, 2006).

The DE centre is designed to satisfy thermal demand of buildings and commercial residences. Calculation of loads for buildings is possible using simulation programs like TRNSYS or Energy Plus, computational models and statistical data (Manfren et al., 2011). However, the loads are measured in small time intervals (hours) which would complicate the optimisation problem. There is lack of methods to systematically simplify the load into time bands with minimum errors i.e. discretising the thermal demand data (Rolfsman, 2004). It has been generally accepted that the systematic design of energy systems of this kind requires optimisation techniques to deal with all the trade-off involved. The optimisation is generally stated in terms of minimising total production costs or maximising revenues (e.g. maximum net present value).