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Optimisation based design of a district energy system for an eco-town in the United Kingdom

C. Weber*, N. Shah

Centre for Process and Systems Engineering, Imperial College, Roderic Hill Building, South Kensington Campus, London SW7 2AZ, UK

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ABSTRACT

The reduction of CO_2 emissions linked with human activities (mainly energy services and transport), together with the increased use of renewable energies, remain high priorities on various political agendas. However, considering the increased consumption of energy services (especially electricity), and the stochastic nature of some of the most promising renewable energies (wind for instance), the challenge is to find the optimal mix of technologies that will provide the energy services, without increasing the CO_2 emissions, but nonetheless ensuring reliability of supply. The focus of this paper is to present the DESDOP tool, based on mixed integer linear optimisation technics, that helps giving insight in the optimal mix of technologies that will simultaneously help decrease the emissions while at the same time guarantee resilience of supply. The results show that while it is not yet possible to avoid electricity from the grid completely (hence nuclear or fossil fuel), CO_2 reductions up to 20%, at no extra costs compared to the business-as-usual case, are easily achievable.

1. Introduction

Since the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, the reduction of the CO_2 emissions linked with human activities has remained a top priority on international, national and regional political agendas. Examples of policies/programs to decrease the CO_2 emissions and/or promote the use of renewable energy sources include: the Kyōtō Protocol and the Energy White Paper of the European Union at an international level; the renewables target in the United Kingdom (15% of the entire energy for electricity, heat and transport in the UK has to be generated from renewable sources by 2020 [1]) at a national level; and various programs on regional and local levels. However, because of the intermittent nature of certain renewable energies like wind or solar energy, introducing large amounts of them in the overall energy mix of a country or region presents a certain number of challenges [2]. The management of the grid and its stability, inaccurate weather forecast (especially for wind [3]), as well as the lack of available storage devices for electricity [2], represent indeed major issues.

Several studies have been conducted to study the influence of the integration of large-scale renewable energy powered technologies (mainly to generate electricity) in the current energy market. Goransson et al. [4] studied the influence of the integration of large-scale wind turbines on the operating strategy of the back-up thermal power plants in Denmark. They showed that because of the introduction of renewable energy sources, thermal plants will have to follow new operating strategies in the future. Streckiene et al. [5] further showed that from base load generation, thermal power plants move over to back-up generators thus requiring technical adaptations and more flexible operation strategies. Moreover, the integration of renewable energies not only poses technical, but also economic challenges as shown by Gross et al. [6] for the UK.

However, the study of meteorological data also brings to light some interesting opportunities for the combination of technologies. Sinden [7] studied the pattern of wind power in the UK from 1970 to 2003 and showed that the wind power availability was over 40% larger in winter than in summer. Combining this result with the obvious fact that solar energy is more abundant in summer than in winter, wind turbines and PV cells could advantageously complement each other. This is true all the more if the PV cells are located primarily in the South of the country, the wind turbines in the North where wind is more abundant, and both are connected to the grid. This example illustrates how an appropriate mix of technologies could partially help mitigate the need for conventional CO_2 emitting technologies to ensure reliability of supply.

The purpose of this paper is to describe a tool adapted from Weber [8] that allows the definition of appropriate combinations of

* Corresponding author. Tel.: +44 20 7594 3387; fax: +44 20 7594 6606.
E-mail addresses: c.weber@imperial.ac.uk (C. Weber), n.shah@imperial.ac.uk (N. Shah).

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Nomenclature

Roman letters - Continuous parameters and variables

A	Area [m^2]
An	Annuity factor [−]
c	Specific costs (distributed energies) [£/kWh]
C	Costs [£/year]
cp_{H_20}	Specific heat of water [kJ/(kg · K)]
COP	Coefficient of performance [−]
D	Duration of a period [h]
$\dot{E}$	Electricity [kW]
F	Maintenance factor [−]
I	Solar irradiation [kW/m^2]
K	Average hourly distributed energy consumed [kW]
$\dot{M}$	Mass flow rate [kg/s]
M	Arbitrary large value
M_{2009}	Current Marshall Swift factor [−]
$\mathrm{M}_{0,i}$	Marshall Swift factor of the reference year [−]
N	Lifetime of a device [year]
Q	Heat (energy) [kWh]
$\dot{Q}$	Heat (power) [kW]
r	Discount rate [−]
S	Design size of a technology/device [kW]
T	Temperature [° C]
v	Velocity [m/s]
$\bar{v}$	Capacity factor of a wind turbine [−]

Roman letters - Integers

x	Binary variable
X	Binary parameter

Greek letters - Continuous parameters and variables

ϵ	Energy efficiency [−]
η	Exergy efficiency [−]
κ	Minimum part load for centralised technologies [−]
λ	Proportional parameter in piecewise linearisations [−]
ρ	Density [kg/m^3]

Superscripts

fix	Fix
hn	Heating network
hp	Heating plant
hr	Heating network return
hs	Heating network supply
max	Maximum
min	Minimum
var	Variable

Subscripts

Be	Betz
cc	Centralised cooling technology
ce	Centralised electricity technology (excluding grid)
ch	Centralised heating technology
CHP	Combined heat and power
cond	Condensor
d	Temperature interval
dc	Distributed cooling technology
de	Distributed electricity technology
dh	Distributed heating technology
DHW	Domestic hot water
e	Distributed energy (including grid electricity)
el	Electric
evap	Evaporator
H	Space heating
i	Device
k	Node
n	Network device (pump, pipes,...)
pv	Photovoltaic
t	Period
th	Thermal
s	Interval in piecewise linearisation
st	Solar thermal
wt	Wind turbine

technologies, including both renewable and non-renewable energy powered technologies, to meet the energy requirements of a small city. The optimisation of energy systems that include one or more technologies to meet the requirements of building energy services (heating, domestic hot water, cooling and electricity) is extensively studied by many authors. The interested reader is referred to the paper published by Connolly et al. [16] for a detailed overview. The majority of these studies can be divided into two main categories. The first category includes studies in which the optimal combination of different technologies to provide at least two different types of energy service to a single building is assessed. See for instance: Weber et al. [9], who analysed the optimal design of a polygeneration system including a fuel cell and an absorption-chiller; Trillat-Berdat et al. [10], who studied an experimental combination of a ground-coupled heat pump with thermal solar collectors; or Ruan et al. [11], who determined the optimal distributed generation technology for different types of commercial building. While these studies all take into consideration the heating and cooling requirements, Weber et al. and Ruan et al. also consider the electricity requirements. On the other hand, various studies have been conducted on the optimisation of district heating systems, a few including district cooling systems like Weber [8], Yamaguchi et al. [12], Thyholt et al. [13], Genon et al. [14] and Möller et al. [15]. These latter studies have the merit of considering more than just one building, and therefore allow for the consumption profiles of different buildings to level out the requirement profiles seen by the heating (cooling) plant. Möller et al. further present a so called heat atlas that includes detailed geographical information on heat demands and existing heating systems to help making decisions on the expansion of existing district heating systems. However, all these studies take into account fewer technologies and/or energy services than the studies in the first category.

The purpose of the District Energy System Design and Optimisation tool presented in this paper, DESDOP, is to combine the features of both above mentioned types of study: the consideration of all the different energy services, combined with a perspective situated at the district level. Moreover, a vast choice of technologies powered by renewable as well as non-renewable energy shall be considered, to understand how both these types of technologies can be best combined to help decrease CO_2 emissions. A similar type of approach combining fossil fuel and renewable energy powered technologies has been adopted by Dicorato et al. [17]. However, Dicorato used high level energy flows to conduct his analysis and focused on energy planning at the regional level rather than at the design level, as it is being done here. Another tool integrating a wider range of urban energy issues (including transport) is currently being developed under the umbrella of the BP Urban Energy Systems project at Imperial College London by