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Distributed energy resource system optimisation using mixed integer linear programming

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HIGHLIGHTS

- A MILP model was created to design a distributed energy resource system for a cluster of buildings.
- The optimal DER system was found to decrease annual costs by 40% and CO_2 emissions by 50%.
- Small wind turbines and biomass boilers were found to be the optimal technologies.
- Energy subsidies are vital because they increase the affordability of low carbon technologies.

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ABSTRACT

In this study a mixed integer linear programming (MILP) model is created for the design (i.e. technology selection, unit sizing, unit location, and distribution network structure) of a distributed energy system that meets the electricity and heating demands of a cluster of commercial and residential buildings while minimising annual investment and operating cost. The model is used to analyse the economic and environmental impacts of distributed energy systems at the neighbourhood scale in comparison to conventional centralised energy generation systems. Additionally, the influence of energy subsidies, such as the UK's Renewable Heat Incentives and Feed in Tariffs, is analysed to determine if they have the desired effect of increasing the economic competitiveness of renewable energy systems.

1. Introduction

In the United Kingdom, the electricity industry accounts for approximately 30% of the national CO_2 emissions (Department of Energy and Climate Change (DECC), 2010). Due to increasingly stringent international and national targets for carbon emissions reductions, numerous strategies have been explored to not only increase the efficiency of electricity generation but also to increase the utilisation of renewable energy sources.

One such strategy is a move away from the conventional system of centralised energy generation and long range energy transmission, and towards decentralised energy generation through the adoption of distributed energy resource (DER) systems. DERs are small-medium sized energy generators that are sited within energy distribution systems, near consumers. They can be made up of a number of power generation technologies including combined heat and power (CHP) systems, photovoltaics (PV), and small wind turbines, as well as energy storage technologies such as lead acid batteries (Ren and Gao, 2010).

DER systems provide numerous advantages over centralised generation. First, by locating generation units closer to the consumer, transmission and distribution losses are minimised. Second, some DER technologies (e.g. CHP) can reuse waste energy to generate additional usable energy streams thus increasing the thermodynamic efficiency and minimising the primary energy consumption. Additionally, DER systems allow for the utilisation of local renewable resources (e.g. indigenous biomass sources), and add a degree of flexibility, resilience, and control to the way in which energy is provided to the consumer (Alanne and Saari, 2006; Alarcon-Rodriguez et al., 2010; Ren and Gao, 2010). However this greater flexibility increases the complexity of energy provision at the district level.

To achieve the maximum benefits of DER systems it is important that the design of these systems takes into account the relative spatial and temporal variations in electricity and heating demands; ensuring that primary energy consumption is minimised through the optimal positioning of generation units and integration of generation technologies. Furthermore, it is vital that the drivers that influence energy planning decisions (i.e. capital costs, electricity and fuel costs, CO_2 emissions, local air quality, legislative targets, etc.) are explicitly incorporated into the analysis, in order to ensure that optimal designs are pragmatic and meet all the requirements of the decision makers.

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The field of distributed energy system planning is expansive, and there is a large body of literature on the design and optimisation of energy systems. Connolly et al. (2010), Keirstead et al. (2012a), and Manfren et al. (2011) have carried out comprehensive reviews of the model formulations and computer tools that are used for analysing the integration of renewable energy into different energy systems. These models can be divided into four general classes: (1) models that simulate the hourly operation of energy supply technologies to assess their technical, economic, and environmental performance; (2) scenario models that analyse the long-term (20–50 year) impacts of specific energy system choices under different scenarios; (3) equilibrium models that use macroeconomic calculations to explain and predict changes in energy supply, energy demand, and utility pricing, typically at the national scale; and (4) operational optimisation models that evaluate how best to integrate and dispatch generation technologies at the district or building scale (Connolly et al., 2010).

Within operational optimisation modelling there is a trade-off between the accuracy of the system model, which explains how the technology performs, and the robustness of the optimisation solution method (Alarcon-Rodriguez et al., 2010). The modelling of energy supply systems can be computationally expensive, as there are many factors that can influence the quantity and quality of the energy generated. However, highly detailed technology modelling may not be pragmatic as it limits the strength of the optimisation models that can be employed to solve the problem. The compromise is to find the point at which model fidelity can be maintained, without having to reduce the complexity of the analysis methods, while also creating a framework that is easily adaptable to multiple contexts (i.e. different spatial scales, or locations). This compromise point depends on the objectives of the overall analysis. In the case presented in this paper, a powerful integrated optimisation tool is required; therefore the technology models have been simplified to a level that allows the optimisation to become tractable. However, additional analyses (e.g. comparison of modelled wind turbine generation outputs with wind turbine power curves) are carried out to ensure that the simplified technology models are representative of technology performance.

Within the set of optimisation models, a mixed integer linear programming (MILP) approach has been particularly favoured because it is flexible and robust enough to manage these aforementioned trade-offs. A number of analysis tools have been developed using the MILP approach, including MODEST, an energy system optimisation model created by Henning et al. (2006), MARKAL, which is based on an economic equilibrium framework and is used for strategic national energy planning in the long term (Seebregts et al., 2001), DER-CAM, the distributed energy resource costumer adoption model developed by the Lawrence Berkeley National Laboratory (Siddiqui et al., 2003), and EnerGIS, a geographical information system coupled with a MILP model to design district heating and cooling networks (Girardin et al., 2010).

In addition to these specific analysis tools, there is a great deal of diversity in the way in which the distributed energy planning problem has been formulated, even within the mixed integer linear programming framework. Some studies deal with a single technology or fuel, and focus on optimising the operation of the system. For example, Chinese and Meneghetti (2005) developed optimisation models for the design of biomass-based district heating networks for an industrial district with an aim to maximise the utility company's profit and also to minimise greenhouse gas emissions. However, the majority of studies deal with a wider set of technologies and analyse the optimal technology selection and unit dispatch (Angrisani et al., 2012; Cho et al., 2009; Dicorato et al., 2008; Hawkes and Leach, 2009; Medrano et al., 2008; Ruan et al., 2009; Soderman and Petterson, 2006). Dicorato et al. (2008) created an energy flow optimisation model for the integration of distributed generation into a regional energy system. The objective function was the minimisation of the energy production cost, and the model employed a multi-period linear approach. Angrisani et al. (2012) analysed the energy, economic, and environmental performance of micro tri-generation systems. Hawkes and Leach (2009) increased the complexity further by constructing a unit dispatch model for a micro grid with the inclusion of electricity and thermal storage.

While the aforementioned models are mainly focused on technology selection, more recent work carried out by Keirstead et al. (2012b), Mehleri et al. (2012, 2013), and Weber and Shah (2011) also include energy distribution in their models. Thus, in these cases, the structure of the DER distribution network is optimised, in addition to technology selection and unit dispatch. However, the addition of distribution increases the number of variables in these studies, therefore requiring the models to be simplified. Whether it is by limiting the number of technologies that they consider, restricting technology installation to a subset of locations, analysing entire years based on seasonal design days, or aggregating the hours of each design day into 5 or 6 periods, assumptions are made in these past studies in order to maintain the tractability of the problem.

This paper contributes to these on-going efforts and builds upon them by introducing the Distributed Energy Network Optimisation (DENO) model, which is both an operational optimisation and scenario model. DENO incorporates the features of the previous work that has been done in this field by using mixed integer linear programming to choose the optimal set of energy generation technologies for a group of consumers at the neighbourhood scale. The model determines the placement of each technology, the structure of the energy distribution network, and the amount of energy distributed between buildings during each time period. As with previous work, seasonal design days are employed. However, rather than aggregating the hours, DENO employs a finer time resolution and uses 24 1-h periods to define each design day. Additionally, a wider set of generation technologies (including two types of CHP, ground source and air source heat pumps, wind turbines, solar thermal collectors, PV, and boilers) and fuels (natural gas and biomass) are allowed in comparison to previous studies, and there are also no limitations on the number or locations of technology installation.

One of the benefits of DENO is that it can be used to analyse trade-offs among different technology and distribution options of a DER system against their economic and environmental impacts. DENO can also be used to assess the impact of strategic policies associated with energy systems, for example conventional centralized energy generation versus distributed systems, or district scale energy centres versus building-scale generators. Most importantly, DENO is grounded within the UK economic and energy policy context. The model explicitly incorporates legislative targets (CO_2 emissions targets and/or renewable energy generation targets) into the modelling framework, while also including the additional revenue that is generated not only from selling electricity back to the grid, but also through the use of the energy subsidies that have been put in place by the UK government. As these energy subsides have been introduced to influence the decisions that investors make with regards to the investment in DER technologies, this allows for the analysis of the effectiveness of these subsidies at improving the environmental impact of energy generation.

The structure of this paper is as follows. The mathematical problem is defined in Section 2, and the model formulation, including the decision variables, objective function, constraints, and key modelling assumptions, is given in Section 3. In Section 4 the optimisation model is applied to a case study in the South of England, with the results and discussion of the outputs analysed in