Optimal Design and Operation of Distributed Energy Systems

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Abstract
This work presents an integrated approach for the design and evaluation of distributed energy resources (DER) systems, based on a detailed Mixed Integer Linear Programming (MILP) model. The mathematical model takes into account energy requirements of the site, local climate data, utility tariff structure, characteristics of the candidate DER technologies (technical and financial) as well as geographical aspects. The model also considers the integration of a heating piping network. The optimal integrated DER system is obtained by minimising an objective function that contains investment, operational, maintenance and environmental costs.

Keywords: Distributed energy resources, heating pipeline network, economic and operation strategies, optimisation, mixed-integer linear programming.

1. Introduction
Increasing concern regarding the depletion of fossil energy resources and the pollution of the environment, as well as the interest in on-site power generation, has increased the importance of developing high-efficiency local energy generation systems, known as distributed energy resources (DER). Compared with traditional central energy supply, DER systems can employ a wide range of technologies including; combined heat and power plants (CHP), photovoltaic systems (PV), small-scale wind turbines and other renewable energy resources. The design of such a system requires the determination of its structure by selecting appropriate equipment from numerous alternatives so that they match energy requirements for a specific customer. It is also necessary to determine the capacity of the adopted equipment as well as the operating strategies, depending on variations in energy demands. Facing such a complex and hard task, a systematic analysis and evaluation procedure is necessary. Currently, a number of plan and evaluation models are available and have recently been reviewed by Hiremath et al. [1]. Furthermore, a lot of research has been reported on this topic [2-3], dealing with the development of optimisation models for the design and management of DER systems from an economic and environmental point of view.

As far as district heating systems is concerned, the majority of the literature focuses on optimisation of the energy conversion technologies and their operational strategies. In
nearly all relevant papers, the design of the heating network is only rarely mentioned, and if ever, a simplified approach is followed, by predetermining the possible routes between the buildings [4-5]. Furthermore, district energy systems, which include heating piping networks, have not received the same level of attention as district heating systems that provide only heating. In this work, an MILP model is proposed for the optimal design of DER systems that integrate PV and CHP technologies with heating piping networks.

2. Problem Description

In this paper, the optimal DER design and operation of a neighbourhood is studied where every dwelling can satisfy its load by a CHP plant, a PV array and a back-up boiler. The CHP plant and PV array are used to meet the electrical demand. The high-temperature exhaust gas of the CHP plant is used to accommodate the thermal load. If the produced heat does not completely satisfy the application needs, the back-up boiler is used for supplying the additional heat load. When the amount of generating electricity by the CHP system and the PV array exceeds the demand of users, the surplus electricity can be delivered back to the grid, otherwise the deficit electricity is supplied by the grid. There is also the possibility of heat exchange between the dwellings through a heating piping network.

In the optimisation problem, the following data are given:

- Dwellings, distances between them, electricity and heat demand profiles
- Capital costs of PV unit, back-up boiler, CHP as a function of its capacity, as well as their operational and maintenance costs, cost of the heating pipeline.
- Technical characteristics of DER technologies
- Electricity and gas tariff prices, prices of selling excess electricity
- Solar irradiance
- Carbon Intensity of electricity and natural gas, carbon tax of CO$_2$.

To determine:

- Allocations and capacities of DER technologies
- Pipeline heating network in the neighbourhood
- Electricity and heat production profiles per dwelling
- Heat transfer amounts through pipeline network
- Main flows of electricity and heat between grid and dwellings

so as to minimise the total annualised cost, including capital, operational and environmental costs.

3. Mathematical Model

3.1 Objective function

The objective function of the model is to minimise the total annualised cost for the residential energy system, as shown in Equation (1):
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\[
\begin{align*}
\min \left\{ C_{TOTAL} = \left( C_{PV}^{INV} + C_{B}^{INV} + C_{CHP}^{INV} + C_{STO}^{INV} \right) \cdot CRF \\
+ C_{PV}^{OM} + C_{B}^{OM} + C_{CHP}^{OM} + C_{STO}^{OM} + C_{GRID}^{PUR} + C_{CARBTAX} - C_{GRID}^{SAL} \right\}
\end{align*}
\]

(1)

where CRF is the capital recovery factor. The cost terms in (1) are explained in Table 1.

Table 1. Specification of cost terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{PV}^{INV} )</td>
<td>PV investment cost, €</td>
</tr>
<tr>
<td>( C_{B}^{INV} )</td>
<td>Boiler investment cost, €</td>
</tr>
<tr>
<td>( C_{CHP}^{INV} )</td>
<td>CHP investment cost, €</td>
</tr>
<tr>
<td>( C_{PV}^{OM} )</td>
<td>Operational and maintenance cost of PV, €/year</td>
</tr>
<tr>
<td>( C_{B}^{OM} )</td>
<td>Operational and maintenance cost of boiler, €/year</td>
</tr>
<tr>
<td>( C_{CHP}^{OM} )</td>
<td>Operational and maintenance cost of CHP, €/year</td>
</tr>
<tr>
<td>( C_{GRID}^{PUR} )</td>
<td>Total cost for purchased electricity, €/year</td>
</tr>
<tr>
<td>( C_{CARBTAX} )</td>
<td>Total environmental cost, €/year</td>
</tr>
<tr>
<td>( C_{GRID}^{SAL} )</td>
<td>Income from selling electricity to the grid, €/year</td>
</tr>
</tbody>
</table>

3.2 Supply-demand relationships

A balance of supply and demand has to be achieved for both heat and electric power at each point in time. The time representation used in this study comprises 12 sample days, one for each month with 24 hourly time periods per day. The electric power and heat balances are shown in Equations (2) and (3), respectively:

\[
\begin{align*}
C_{Load}^{ELEC}_{i,m,h} &= E_{GRID}^{i,m,h} + E_{PV}^{i,m,h,SELF} + E_{CHP}^{i,m,h,SELF} \quad \forall i, m, h \\
C_{Load}^{HEAT}_{i,m,h} - \sum_{j \neq i} (QH_{j,i,m,h} - QH_{i,j,m,h}) &= H_{B}^{i,m,h} + \left( E_{CHP}^{i,m,h,SELF} + E_{CHP}^{i,m,h,SAL} \right) \cdot HER \\
&\quad \forall i, m, h
\end{align*}
\]

(2)

(3)

where \( C_{Load}^{ELEC}_{i,m,h} \) and \( C_{Load}^{HEAT}_{i,m,h} \) are the customer electricity and heat loads (kW), respectively, \( E_{GRID}^{i,m,h} \) is the purchased electricity from the grid (kW), \( E_{PV}^{i,m,h,SELF} \) and \( E_{CHP}^{i,m,h,SELF} \) is the electricity generated from the PV and CHP unit (kW) for self use, \( QH_{i,j,m,h} \) is the heat transfer from building \( i \) to \( j \) (kW), \( H_{B}^{i,m,h} \) is the heat generated by
the boiler (kW), $E_{i,m,h,sAL}^{\text{CHP}}$ is the excess electricity sold by the CHP unit (kW) and HER is the heat-to-electricity ratio. The subscripts $i, m, h$, refer to the dwelling, month and hour, respectively. Additional constraints are implemented to describe the performance characteristics of the various units, which are not presented here due to space limitations.

4. Illustrative Example

The proposed mathematical model is applied to a neighbourhood that consists of 5 buildings. Residential CHP and PV systems are considered for investment. The project is for 20 years, and an annual interest rate of 7.5% is used. Apart from electricity and heat demand profiles, other important inputs that are taken into account are:

- Market data such as electricity and fuel tariff rates
- Characteristics of the candidate DER technologies
- Cost of the heating pipeline
- Distances between any pair of buildings

Concerning the capital costs of CHP plants, these are assumed to be available at 5 different capacities: 5, 10, 20, 50 and 100 kW.e.

The following two scenarios have been studied for analysis and comparison purposes:

- Scenario A: Conventional system (Electricity load is satisfied by utility grid and thermal load by gas boiler).
- Scenario B: DER system with CHP and PV units and heating pipeline network.

The problem is formulated as an MILP model, which is modelled and solved in GAMS, using the CPLEX 11.1.1 solver. The optimality gap was set to 5%. The optimal system configurations for the two scenarios are presented in Figure 1.

The adopted heating pipeline network is: $i_5 \rightarrow i_4$, $i_4 \rightarrow i_2$, $i_3 \rightarrow i_2$. The total annualised costs for Scenarios 1 and 2 are 19398.768 €/year and 11452.061 €/year, respectively, which shows a reduction of 41% when adopting the DER technology. The breakdown of the optimal annualised total costs for both scenarios is given in Figure 2. By the environmental point of view, the adoption of DER technologies, PV units and heating
pipeline network leads to a 58% reduction of $CO_2$ emissions (Scenario A: 41183 kg/year, Scenario B: 17385 kg/year).

![Figure 2. Breakdown of the optimal total annualised cost (€) for scenarios A and B](image)

5. Concluding Remarks

In this paper, an MILP model has been proposed for the design and evaluation of distributed energy systems. Besides determining the optimal combination and allocation of DER technologies and their operation strategies, the economic and environmental impacts have also been discussed. As an illustrative example, the optimal DER system of a neighbourhood of five buildings has been examined under 2 different scenarios (Conventional; and DER system with CHP and PV units together with heating pipeline network). The results clearly illustrate the advantages of DER technologies.

6. Acknowledgements

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References