INTEGRATED MODELLING OF GAS AND ELECTRICITY DISTRIBUTION NETWORKS WITH A HIGH PENETRATION OF EMBEDDED GENERATION

Salvador ACHA
Imperial College London
salvador.acha@imperial.ac.uk

Carlos HERNANDEZ-ARAMBURO
Imperial College London
c.a.hernandez@imperial.ac.uk

ABSTRACT

Gas-based combined heat and power (CHP) has matured enough to be regarded as the next evolutionary step in promoting energy efficiency use in the urban environment. Although its potential market is increasing, little research has been conducted into the combined technical effects that a high penetration of these units may have on both natural gas and electric (G&E) distribution networks. This paper presents a power flow tool that performs a simultaneous assessment on some technical impacts that a high penetration of heat-driven cogeneration units may have on G&E networks. A case study is presented and results show that as expected, the gas demand increases as well as the losses associated with its delivery, while the opposite effects occur in the electrical system. However, less evident is the load profile variations distribution networks will experience and that overall energy losses will vary according to the CHP penetration and the type of technology used. The study shows that an integrated G&E analysis offers a fresh perspective in quantifying the effects cogeneration technologies will have on energy distribution networks.

INTRODUCTION

CHP technology has matured in the last few years to such a degree that certain devices are nowadays available in the market as boiler substitutes for domestic and commercial consumers [1]. These units run on natural gas and usually 60 to 80% of the fuel they consume is used to generate useful heat and electricity. Due to the above reasons, natural gas is seen as the fuel of choice for a developed country committed to the environment [2]. For instance, the UK's goal is to have an installed CHP capacity of 10 GW_{el} by 2010 [3]. Though energy service networks have traditionally evolved separately from one another, the progress of cogeneration has the potential to create a powerful synergy that increases the overall efficiency of heat and power delivery to final consumers. This means interrelationships between G&E infrastructures have to be identified and quantified so integrated decisions can bring benefits to the investment made by network operators [4].

Most of the existing publications looking at the interactions between G&E networks, e.g. [5] and [6], focus on issues at a transmission level. The abundance of literature in this field is because the "dash for gas" in centralised power systems is a much more mature subject than at a distribution level. Nonetheless, encouraging work [7], [8] has been carried out to solve natural gas load flow problems by employing optimal power flow techniques. These papers formulate analogies among the energy networks which were first introduced by Osiadacz [9]. In addition, there are other publications [4], [10] which suggest a growing concern in acknowledging and exploring the interdependence between G&E infrastructures. Reference [4] discusses some benefits, aside from the economic issues, that a combined study of the networks may bring:

1) Documentation for strategic planning activities.
2) Information of risk-sharing supply and capacity decisions between utilities and regulators.
3) Identify where and when to allocate CHP to avoid reinforcement costs in the electric networks.
4) Insights in reliability levels for G&E systems.

To address the challenge of analysing the interactions between G&E distribution networks this paper introduces an integrated power flow model where CHP units serve as a link between both networks. The work first discusses the gas network modeling theory, which is later used to provide a unified framework to solve load flow problems in conjunction with the electrical networks. Then the paper follows by presenting a case study that shows how cogeneration devices influence key operating parameters in each network (such as voltage profiles in electric networks), the load profiles seen from the distribution supply point, and the overall G&E energy losses. Results from the simulation demonstrate the relevance of the power flow tool in evaluating and quantifying the effects that embedded generation technologies have on the delivery of energy to consumers.

GAS SYSTEM MODELLING

As gas flows through the network, energy and pressure are lost due to friction and heat transfer. The purpose of the gas load flow problem is to determine the pressure values in all the consumption points and the rates of flow for all the pipes in the network. The known input data are the load requirements in the system, the pressure values at source nodes, and the connectivity matrix. An iterative process is used to solve the set of non-linear equations the problem presents. Hence, due to its effectiveness, the Newton-Raphson (N-R) nodal method is applied to solve the gas load flows in a similar way as for electric power networks.

The steady-state flow rate of gas in a pipe is described by many formulas, but none has the complete acceptance of academia and industry [11]. This is because the effects of friction are difficult to quantify and this has created formula variations in the literature. The following model is usually applied for network analysis in the gas industry. The derivation of the general gas flow equation employed here is based from Weymouth's equation and involves a number of simplifying assumptions which include:

1) The temperature of the flow remains constant.
2) No speed variations of the flow.
3) Constant gas density throughout the network.
4) Constant friction factor for all pipe lengths.

Equation 1 states that for any pipe *k*, the flow equation from node *i* to node *j* can be expressed as:

$$\phi\left[(Q_n)_k\right] = K_k\left(Q_n^{m_1}\right)_k \qquad (1)$$

Where:
$\phi[(Q_n)_k]$ = flow function for pipe k
$(Q_n)_k$ = flow in pipe k
m_1 = flow exponent based on the pressure level of the network
K_k = friction factor for pipe k which is equal to $11.7 \times 10^3(L_k/D_k)$; L_k is length of pipe in meters; D_k is diameter of pipe in millimeters

For a gas network the nodal formulation is equivalent to Kirchhoff's current law (KCL) in electric networks. Equation 2 is a set of non-linear equations for a proposed network which follows the KCL principle. Subsequently, an iterative process is used to obtain the nodal pressure values.

$$F(P) = L - A_1 Q = 0 \qquad (2)$$

Where:
$F(P)$ = vector of nodal flow balance in the network as a function of the nodal pressures
L = vector of loads of dimension n nodes
A_1 = branch-nodal incidence matrix
Q = vector of the flows in the branches of dimension m pipes

GAS AND ELECTRIC NETWORK ANALOGIES

Understanding the basic characteristics of the gas system has allowed to build analogies with the electric system. Table 1 gives an overview of the main terms considered when conducting the integrated G&E power flow.

Table 1. Analogous variables with its respective SI units

Aspect	Gas system	Electric system
Potential	Pressure (N/m^2)	Voltage (V)
Flux	Flow (m^3/s)	Current (A)
Power	Pressure*Flow (W)	Voltage*Current (W)
Power loss	ΔPressure*Flow (W)	ΔVoltage*Current (W)
Resistance	Friction factor (k)	Impedance (Ω)

Nodes in a gas network can be of two types, either a *load node* or a *pressure node*. For a load node the amount of power required is initially known and the pressure value of the node is what needs to be determined. In electrical systems they are similar to a PQ or "load bus". On the other hand for a pressure node the potential is fixed and they serve as a reference for other nodes, the flow injection going through this type of node is what needs to be calculated. In electrical systems they would be analogous to having a PV or a "slack bus". Table 2 describes a step by step summary of the integrated G&E power flow process. Once established the unified framework for energy network analysis it is possible to link both systems by introducing CHP devices into the integrated power flow program.

G&E LOAD FLOW CASE STUDY

The case study objective is to assess the technical impacts of heat-driven cogeneration units on both networks during a typical UK winter day by varying the degree of penetration. The integrated power flow program has been coded in computing software and tested in an urban 15 node radial network that serves both G&E services as seen in figure 1. The network features are representative since they have been taken from specialised distribution network studies. The electric network characteristics are taken from [12], while the gas counterpart comes from [11]. The substation voltage is 11 kV, while the base pressure is 7 bars.

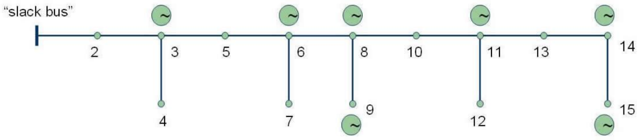

Figure 1. 15 node radial networks used for G&E load flow test.

The input data used to run the power flow calculations can be seen in figures 2 and 3. They illustrate the G&E load profiles from the "slack bus" in a typical winter weekday [13]. The gas demand can be up to 8 times higher than power demand at certain moments of the day. Nevertheless, the overall daily average is approximately a 4 to 1 heat to power ratio. Another interesting characteristic when comparing the profiles is the temporal shift of peak demand that occurs before for the gas network than for its electric counterpart during the early morning and afternoon.

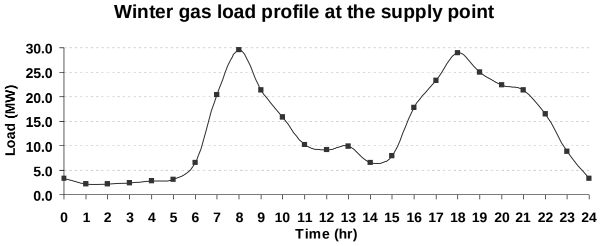

Figure 2. Gas load profile used to conduct the case study.

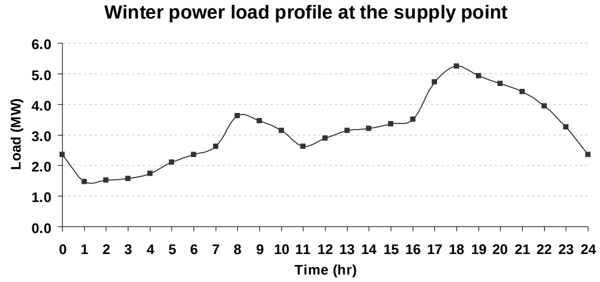

Figure 3. Power load profile used to conduct the case study.

The spread of CHP only occurs in 7 nodes of the network and the assessment was carried out when 10, 25, and 50 percent of the customers adopt the technology. All of these devices operate under thermal demand requirements and the power generated is considered an additional benefit. Wherever there is no CHP present it is assumed boilers with 80% efficiency satisfy the remaining heat demand. Table 3 displays the characteristics of the CHP units used for the simulation, in which all the models have the same power capacity.

Table 2. Description of how electricity and gas load flows are calculated using the Newton-Raphson method

Electric system power flow procedure	Gas system power flow procedure
INPUT DATA **0.** Determine per unit base values for the system regarding power, voltage, impedance, and current as well as the tolerance value "ε" which the algorithm needs to satisfy regarding power mismatches. **1.** Obtain number of nodes and classify them according to their type (*PQ, PV, Slack*). **2.** Establish line connections in the network with its respective *length* and *impedance* specifications so the bus admittance matrix can be formed. **3.** Initialise P_i, Q_i, V_i, δ_i variables with known values for *PQ* and *PV* buses.	**INPUT DATA** **0.** Determine per unit base values for the system regarding power, pressure, friction factor, and flow as well as the tolerance value "ε" which the algorithm needs to satisfy regarding flow mismatches. **1.** Obtain number of nodes and classify them according to their type (*load, pressure, source node*). **2.** Establish pipe connections in the network with its respective *friction factors* specifications so the incidence matrix can be formed. **3.** Initialise flow and pressure variables with known values for pressure and load nodes.
INITIAL CALCULATIONS **4.** Calculate initial nodal currents I_i, obtain nodal voltages V_i, and determine the new P_i, Q_i values in order to find the ΔP and ΔQ power mismatches. **5.** If any nodal power mismatch error is over the tolerance value "ε" the iterative process begins.	**INITIAL CALCULATIONS** **4.** With the flow estimations and *friction factors* determine pressure changes in each pipe. The pressure changes give new pressure values at all nodes which alter the flows going to each node. **5.** If any nodal flow error is over the tolerance value "ε" the iterative process begins.
ITERATIVE PROCESS **6.** The Jacobian matrix is formed and calculated. **7.** The changes in nodal voltage magnitude V_i and angle δ_i are determined and the new values are updated by using equation 3 $\left[\frac{\Delta\delta}{\Delta V}\right] = [J]^{-1}\cdot\left[\frac{\Delta P}{\Delta Q}\right]$ (3) **8.** Based on the new voltage values, re-calculate new nodal currents I_i, determine the new P_i, Q_i values and find the nodal power mismatches (ΔP and ΔQ) in each bus. **9.** Repeat steps 6 to 9 until every nodal power mismatch value is within the accepted margin "ε".	**ITERATIVE PROCESS** **6.** The Jacobian matrix is formed and calculated. **7.** The changes in nodal pressures are determined and the new pressure values are updated by using equation 4 $\Delta P_{re} = [J]^{-1}\cdot[-F(P_{re})]$ (4) **8.** Based on the new pressure values, re-calculate the flows through pipes and determine the flow mismatch (ΔF) in each node. **9.** Repeat steps 6 to 9 until every nodal flow mismatch value is within the accepted margin "ε".
OUTPUT DATA **10.** Nodal voltage V_i and angle δ_i are determined in the system. **11.** Power P_i, Q_i flowing through each line and its respective voltage drops are known. **12.** Power P_i, Q_i generated by the "slack bus" is determined. **13.** Power losses P_i, Q_i in the system are defined.	**OUTPUT DATA** **10.** Pressure value and flow balance is confirmed at each node in the system. **11.** Flow through each pipe and the pressure differences between nodes are known. **12.** Power flowing through each line as well as its respective power losses is calculated. **13.** Power provided by the "Slack node" is determined. **14.** Power losses in the system are defined.

Table 3. Operating parameters of CHP units modeled

CHP Technology	Thermal Efficiency (%)	Thermal Capacity (kW_{th})	Power Efficiency (%)	Power Capacity (kW_{el})
Stirling	70	7.2	12	1.2
Reciprocating	55	3.0	25	1.2
Fuel cell	45	1.2	45	1.2

RESULTS FROM THE CASE STUDY

Since all the CHP technologies have a lower thermal efficiency than boilers, results show the gas demand increase as well as the power losses associated with its delivery. Meanwhile, the opposite effects occur in the electric system due to the production of electricity by the users. Hence, the pressure values in the gas network drop, while the voltage levels in the electric network rise. This difference will vary with the heat to electricity ratio (HER) of the unit being assessed. In this specific case study the operating parameters do not vary much as table 4 indicates. Therefore, it can be said that CHP technology in this particular example does not represent a great threat to the operability of G&E networks. Nevertheless, attention should always be given to these parameters when cogeneration studies are conducted to guarantee that no statutory limits are breached.

Table 4. Minimum pressure and voltage values for node 15 in the network at a 50% CHP penetration

Variable in PU	pre-CHP scenario	Stirling engine	Reciprocating engine	Fuel cell
Pressure	0.9767	0.9749	0.9741	0.9750
Voltage	0.9697	0.9747	0.9750	0.9750

Consumers will theoretically have the same energy demands when they posses a CHP unit, but the fact they can generate their own electricity could create considerable changes in the load profiles distribution networks will visualise from their supply point. Figures 4 to 6 illustrate the power demand variations that will occur as the different CHP technologies begin to gain presence in the network. The greatest load variations will naturally occur as the penetration is more prominent and at moments of high thermal demand, in this case from 6 to 8 am and 3 to 5 pm.

Additionally, the base to peak demand ratio in all the profiles is linked to the HER of the unit being assessed.

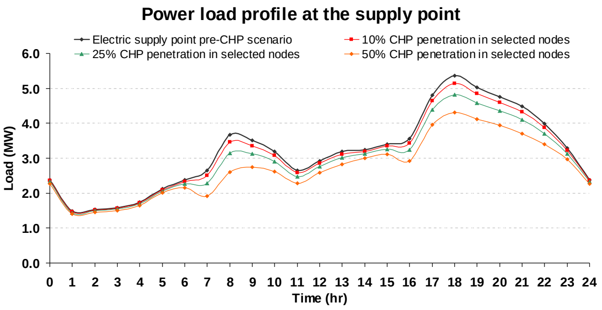

Figure 4. Load profile when Stirling engines are used.

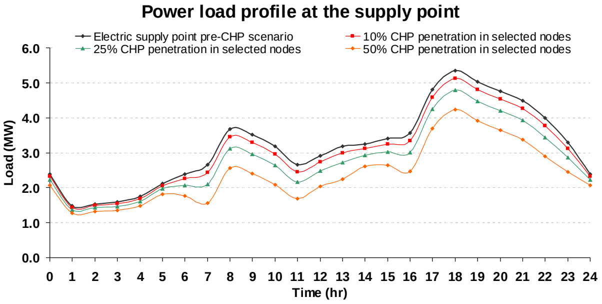

Figure 5. Load profile when reciprocating engines are used.

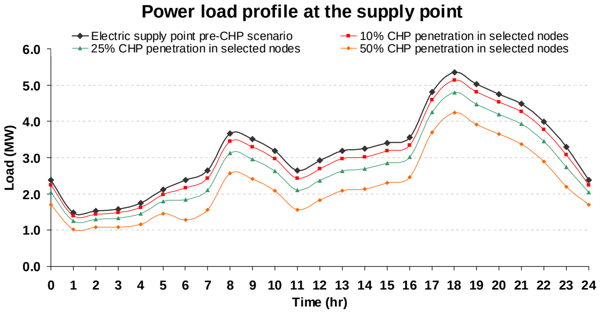

Figure 6. Load profile when fuel cell engines are used.

Figure 7 summarizes how each cogeneration technology will influence energy losses in G&E networks. It can be seen that CHP technologies with lower HER have a greater impact on the minimization of losses as the penetration is gradually increased. This is because the reduction in electric losses that CHP units provide outweighs the increase in gas losses. Therefore, fuel cell technology looks as the most promising regarding reduction of energy losses.

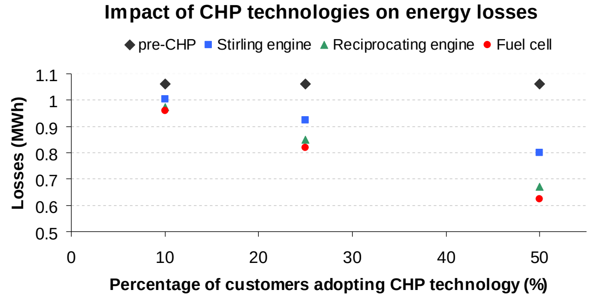

Figure 7. Each CHP technology will impact losses differently.

CONCLUSION

This paper offers an integrated G&E power flow tool that broadens the technical effects that a high penetration of embedded generation might have on energy distribution networks. Gas system modeling has been explained and analogies with the electric system drawn. Using the N-R nodal method a unified framework for steady-state G&E power flows has been established. A case study has been presented in which the effects of different heat-driven CHP technologies have been evaluated in a typical winter day. Results show that the degree of penetration and the HER of each CHP technology will impact differently the operating parameters, load profiles, and energy network losses. Further research in this field is needed in order to comprehend the benefits and drawbacks that each CHP option brings to the stakeholders involved in the delivery of energy.

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