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Joint Symposium on Innovation in Energy Systems

“Integrated modelling of gas and electricity distribution networks with a high penetration of embedded generation”

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Structure of presentation

- Introduction
- Context of the energy networks problem
- Modelling of gas networks
- Gas and electricity load flow analogy
- Present a combined load flow example
- Further work and conclusions

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Introduction

- **What benefits could be achieved if cities organised themselves to integrate their energy use?**

- Urban energy service networks have traditionally evolved separately.
- The coupling of gas and electricity distribution systems through cogeneration represents a powerful ***synergy*** opportunity for energy delivery.

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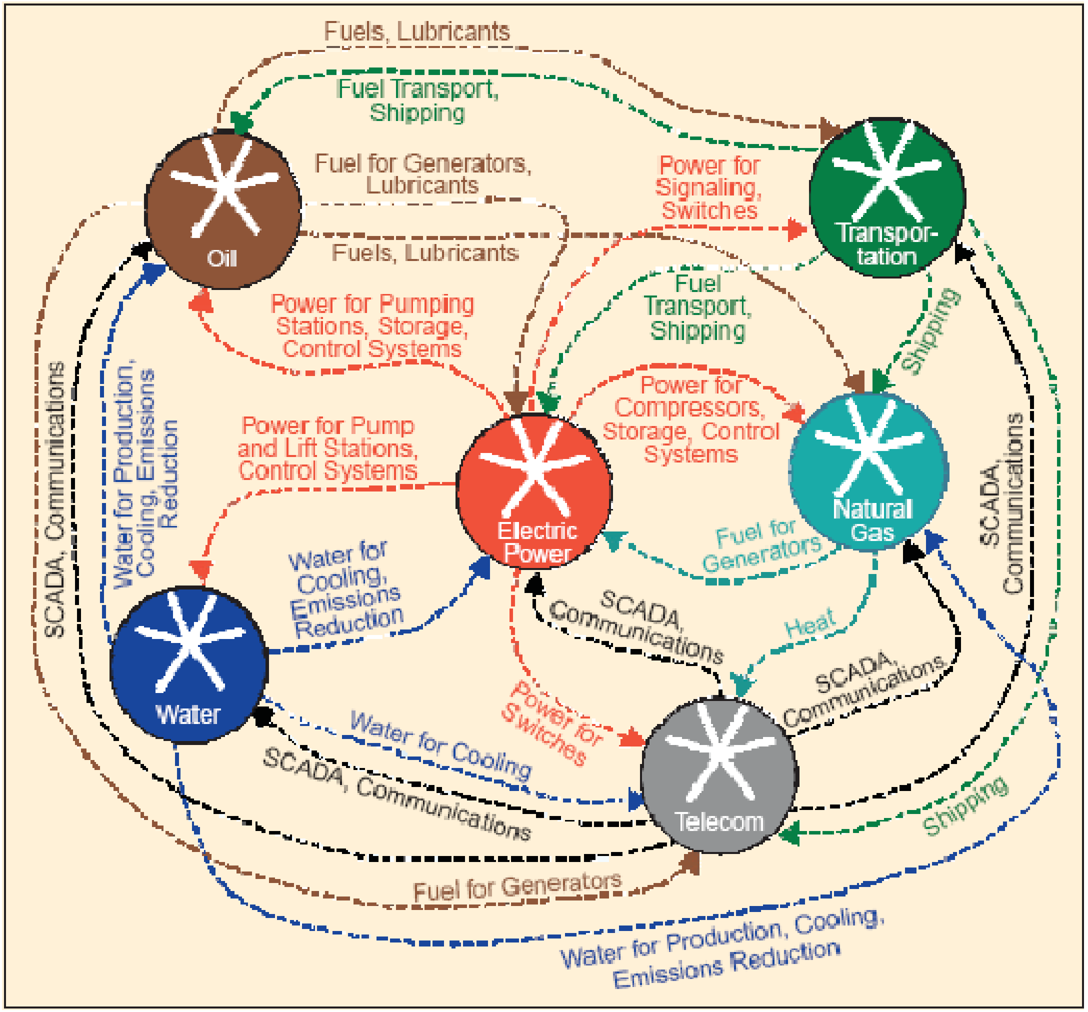
Introduction

- **But to what degree are gas and electricity networks complementary?**

- The combined technical effects that cogeneration can have on both networks is unexplored in academia.
- Understanding the **interactions between infrastructures** is important for different stakeholders.

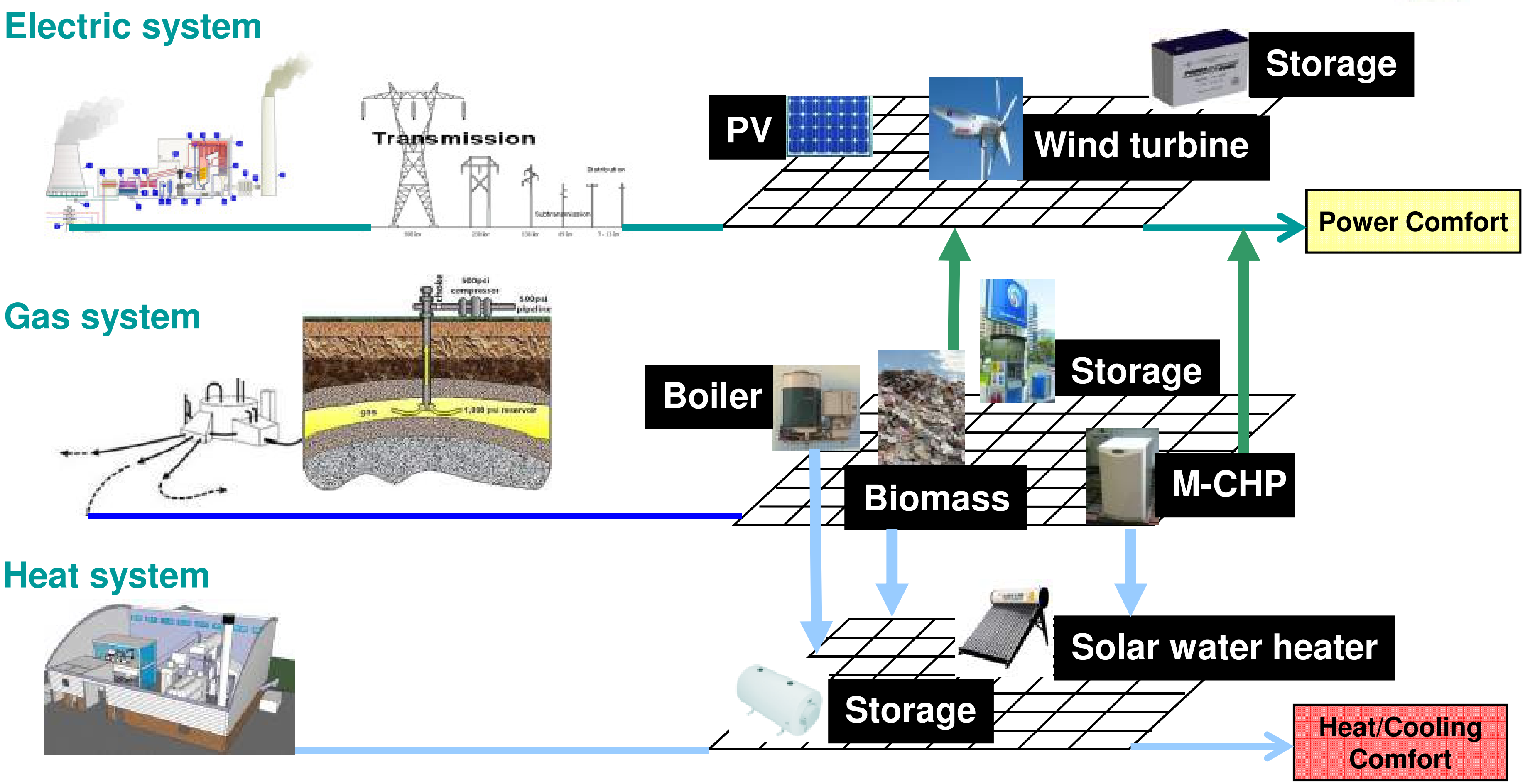
Urban energy systems

- ***Interdependency*** is "a bidirectional relationship between infrastructures in which the state of each infrastructure is influenced by the state of the other" [1].



Examples of infrastructure interdependencies.
Source [2]: IEEE Control Systems Magazine.

Energy networks



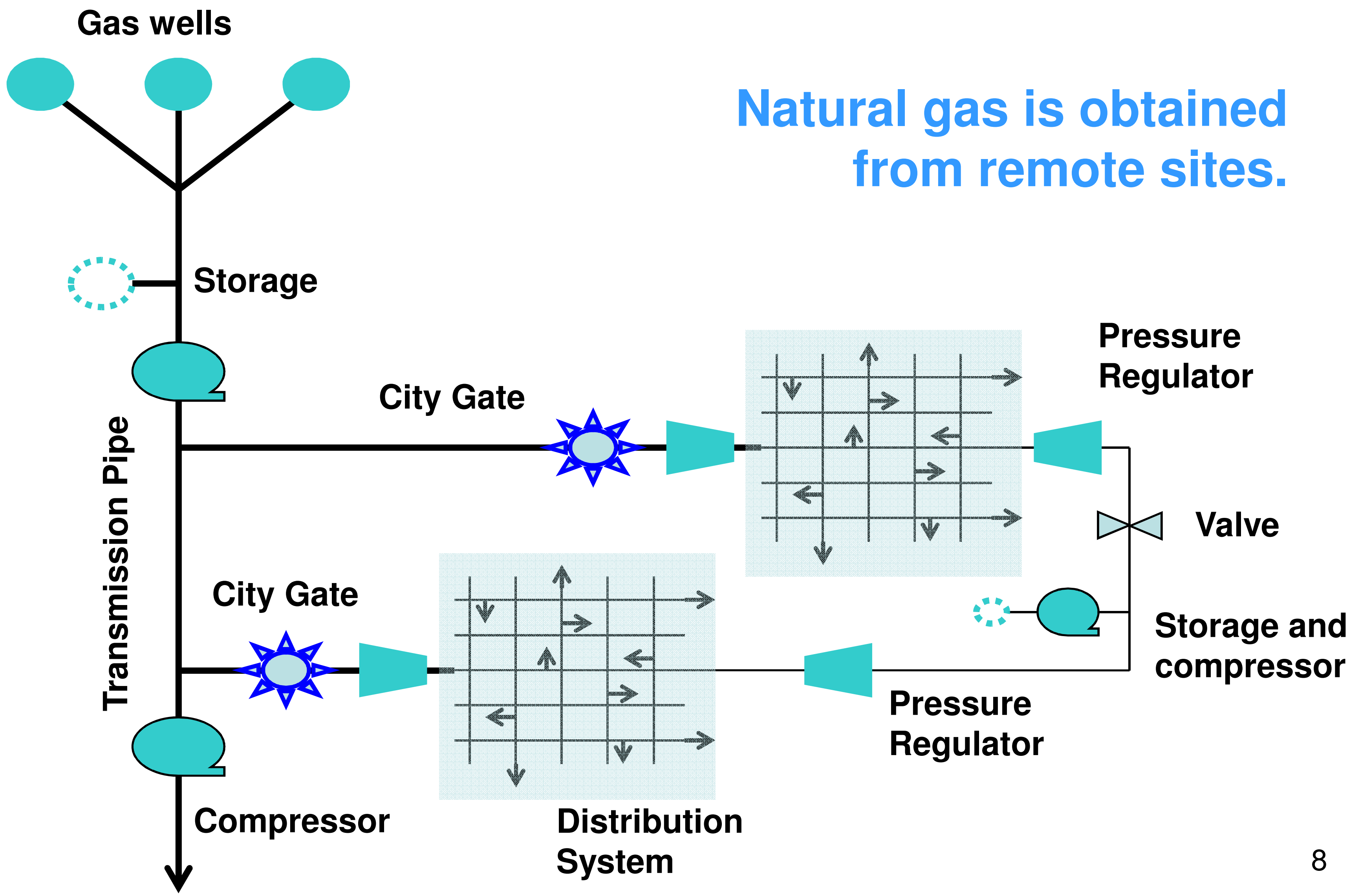
Omitting interdependencies will limit the validity of independent analysis.

Modelling energy networks

- How do we begin to analyse energy flow interactions?
- The research has begun by developing a "*steady-state combined gas and electricity power flow program*".
- Therefore, it has been necessary to gain familiarity with the gas system.

Gas system description

Natural gas is obtained from remote sites.



Gas and electricity analogy

Term	In gas	In electricity
Potential	Pressure	Voltage
Flux	Flow	Current
Power	Pressure*Flow	Voltage*Current
Power losses	ΔPressure*Flow	ΔVoltage*Current
Resistance to flux	Friction Factor	Impedance
Connectivity matrix	Branch-nodal	Admittance

Analogies show many similarities but they do not end there.

Gas and electricity analogy

Component	In gas	In electricity
Branch	Pipes	Feeders
Source node	Pressure node	PV bus
Consumption node	Load node	PQ bus
Step down mechanism	City gate	Substation
Devices	Compressor/ Pressure regulator	Tap changer/ Voltage regulator

The method to find a solution is very similar as well.

The gas flow problem

- The gas load flow problem consists in calculating the ***values of node pressures and flow rates*** in the individual pipes for known values of source pressure and of gas injections at load nodes [3].

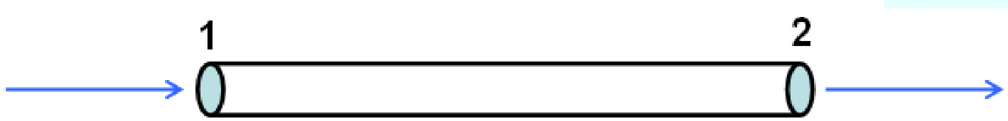
Formulation of gas equations

- For any pipe *k*, the flow equation from node *i* to node *j* can be expressed in terms of pressure difference [4].

Where:
m_1 = flow exponent
K_k = friction factor
P_i = sending node
P_j = receiving node
$(Q_n)_k$ = flow in pipe k

$$(Q_n)_k = \phi'(\Delta P_k) = \left(\Delta P_k / K_k \right)^{1/m_1}$$ **Eq. 1**

$$\Delta P_k = P_1 - P_2 = k_k Q_k^2$$ **Eq. 2**



Mechanical energy becomes thermal energy due to friction.

Formulation of gas equations

- A set of non-linear equations is made to solve for nodal flows in function of nodal pressure values, KCL equivalent.

$$F(P) = L^{total} - A_1 Q = 0 \qquad \textbf{Eq. 3}$$

- The Newton-Raphson nodal method is applied to solve the set of equations.

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Load flow analogies

Electric system	Gas system
Set-up and initial data	
Determine per unit (PU) values Define "ε" tolerance for power and flow mismatch Classify node types Build connectivity matrix Initialise problem with assumed and known values	

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Initial calculations

Electric system	Gas system
Calculate nodal currents	Calculate nodal flows
Determine nodal voltages and complex power values	Find pressure changes in pipes and update nodal pressures
Obtain power mismatches	Obtain flow mismatches
If any mismatch is greater than "ε", begin iterations	If any mismatch is greater than "ε", begin iterations

Analogies between electric and gas load flows.

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Iterative process

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Electric system	Gas system
Jacobian matrix is calculated	Jacobian matrix calculated
Changes in voltage and angle are determined	Changes in pressure are determined
$\begin{bmatrix} \frac{\Delta\delta}{\Delta V} \end{bmatrix} = [J]^{-1} \cdot \begin{bmatrix} \frac{\Delta P}{\Delta Q} \end{bmatrix}$	$\Delta P = [J]^{-1} \cdot [-F(P)]$
Update nodal voltages, currents and power mismatch values	Update nodal pressure and flow values
If any power mismatch is > "ε", recalculate the Jacobian	If any flow mismatch is > "ε", recalculate the Jacobian

Analogies between electric and gas load flows.

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Output data

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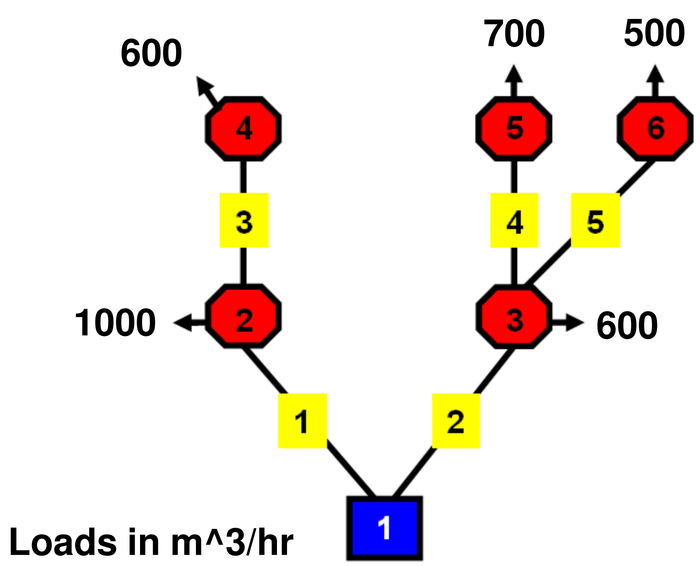
Electric system	Gas system
Voltage and angle values are determined for each bus	Pressure values are determined for each node
Power generated by slack bus and power flowing in each line is determined	Power generated by the slack node and flow in each pipe is determined
Power losses in the electric system are determined	Power losses in the gas system are determined
The power data collected is expressed in energy terms	

Analogies between electric and gas load flows.

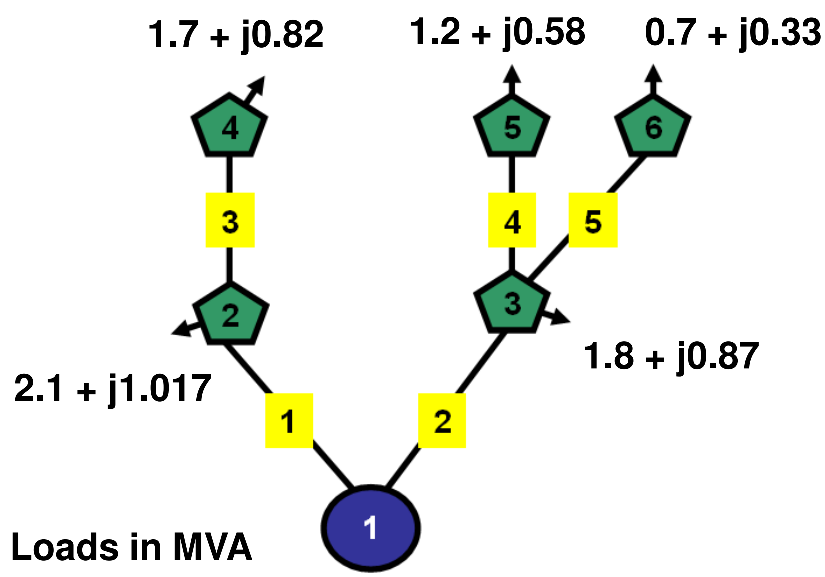
Example

- Objective is to show the combined technical effects that CHP has on the gas and electric networks on a typical winter day.



GAS NETWORK

Base pressure = 7 bar



ELECTRIC NETWORK

Base voltage = 11 kV

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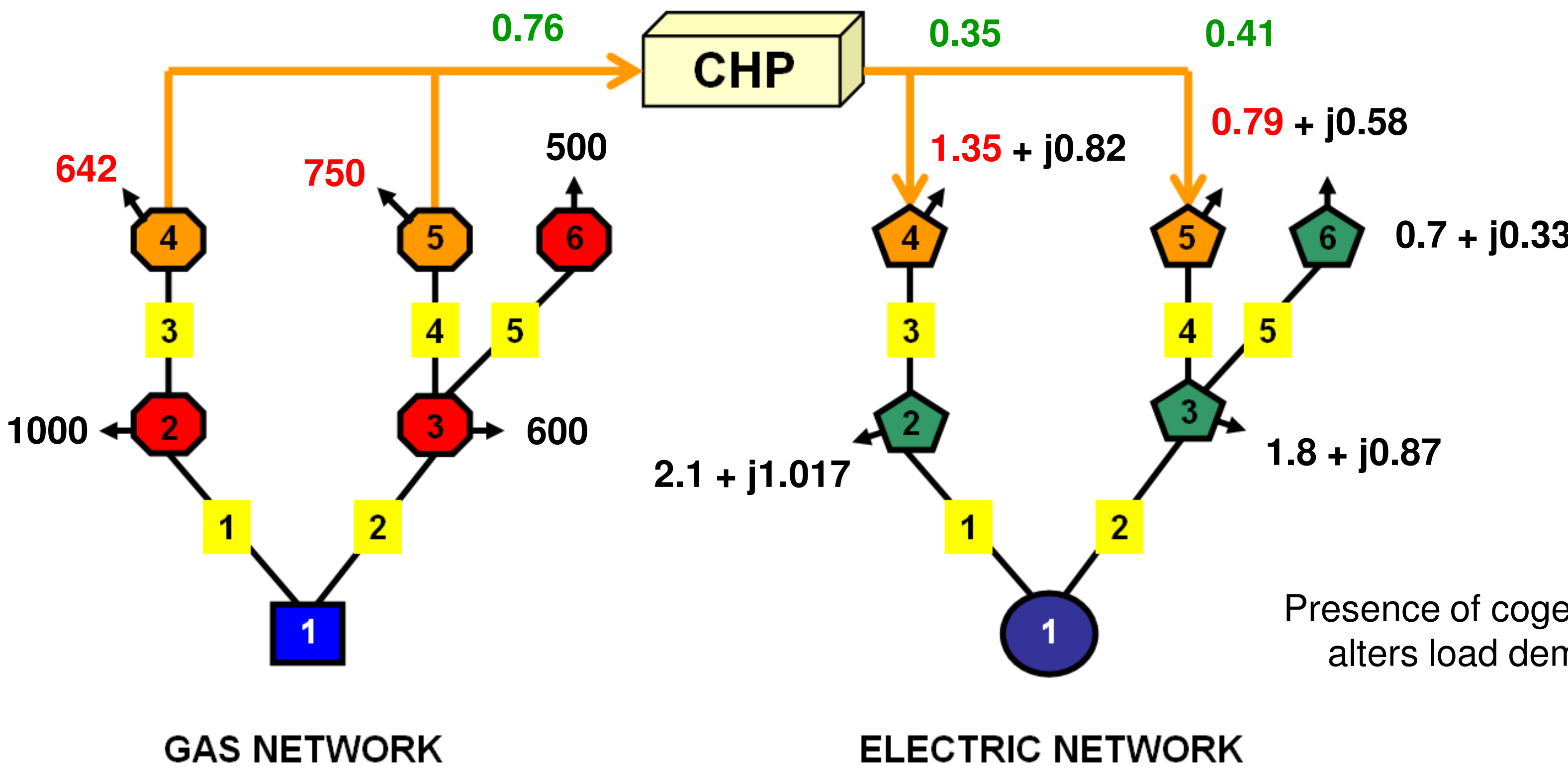
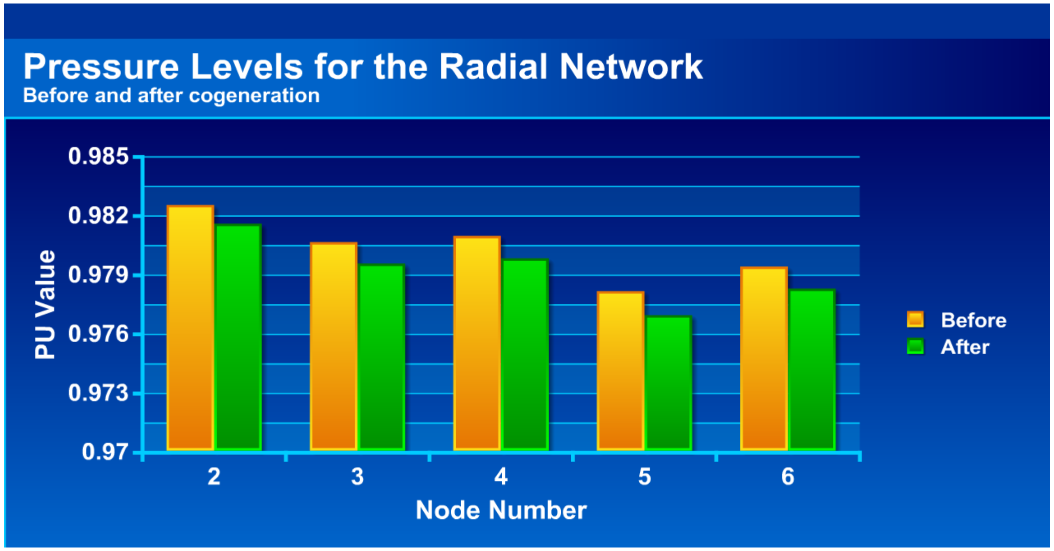
Example

- A 50% of the heat demand in nodes 4 and 5 is provided by gas fuelled Sterling engines.



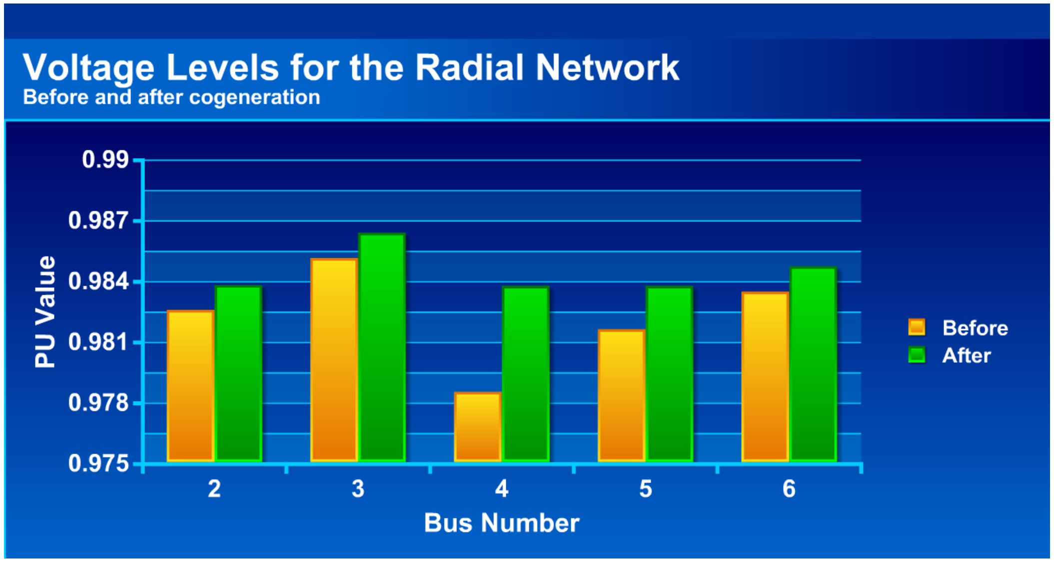
Presence of cogeneration alters load demands

Operating conditions

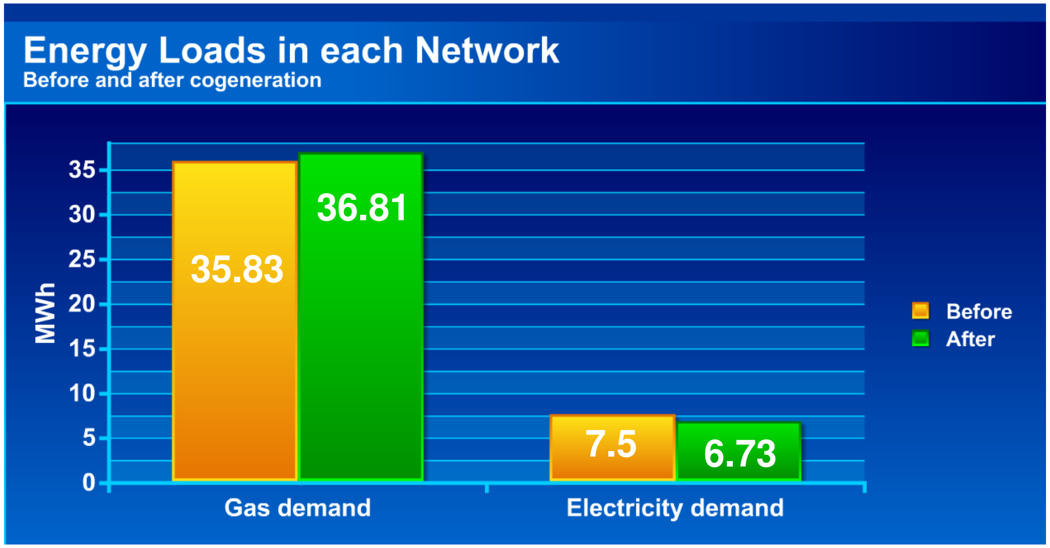


A higher demand of gas for nodes 4 and 5 reduces the pressure levels throughout the network.

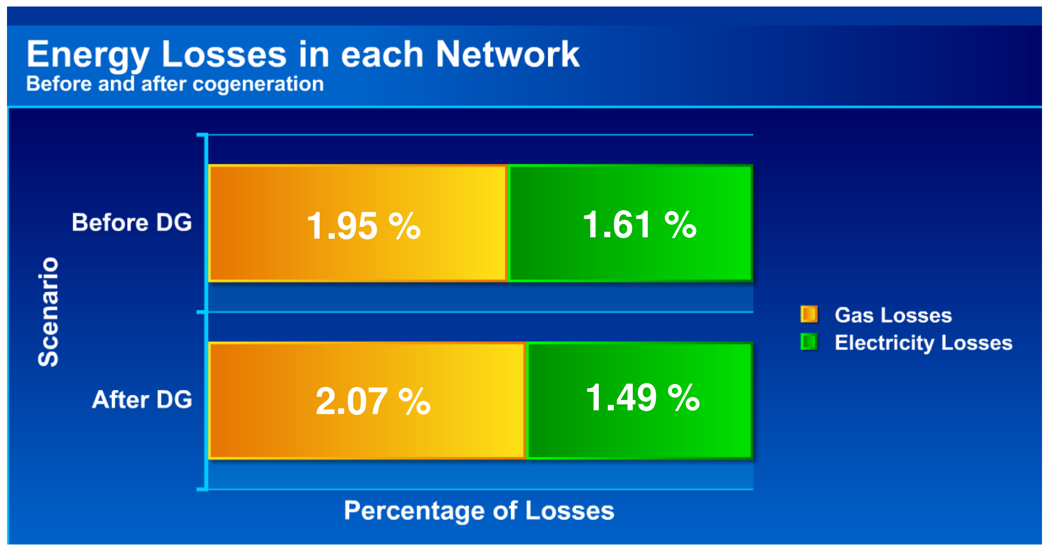
Electricity being produced with cogeneration translates into less demand for power for the DNO and a voltage raise throughout the network.



Energy demand and losses



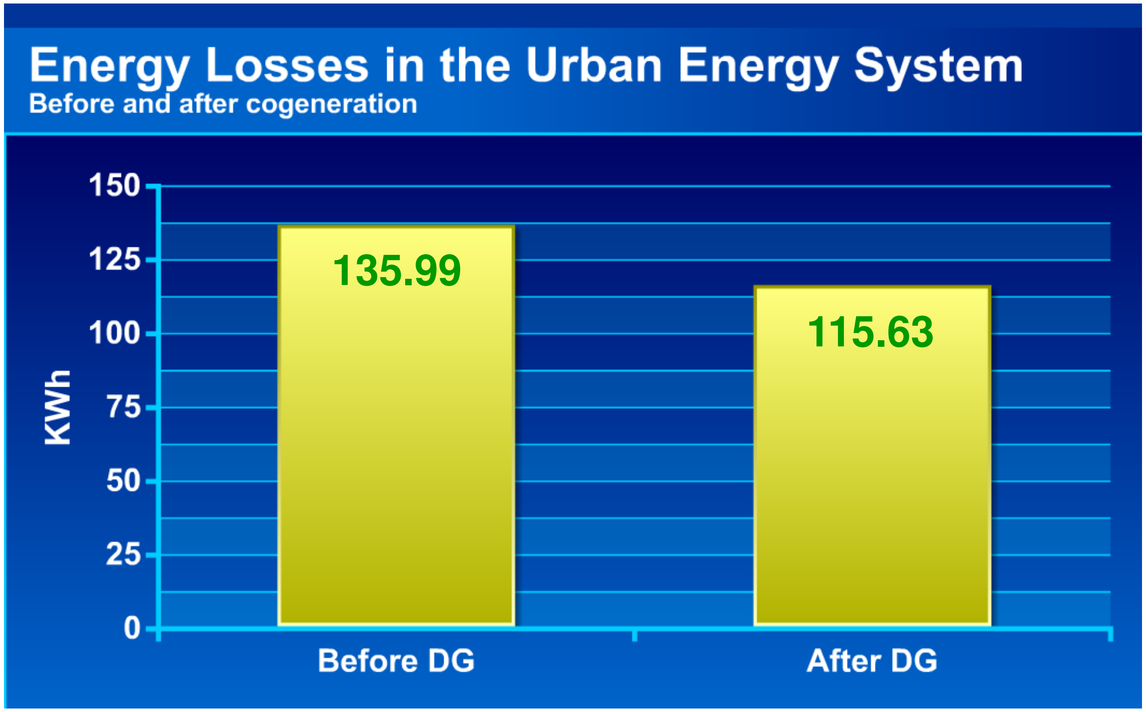
The loads that network operators need to satisfy vary with the introduction of cogeneration.



The energy losses in the gas network increase while the losses in the electric network are reduced.

Quantifying the common welfare

- The total energy saved translates into a common welfare for many parties involved. We need to asses the benefits.



By introducing cogeneration the difference in energy losses is of **20.36 kWh**.

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Further work

- Quantify the energy saved (common welfare) in economic terms.
- Develop more case scenarios under different cogeneration operation modes.
- Asses the load perspective both DNO's will have from the use of cogeneration.
- Possibility to add water or heat networks.
- Optimise the power flow tool by respecting technical constraints of the systems.

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Conclusion

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- A common framework for gas and electricity network studies has been made.
- A simultaneous gas and electric load flow with embedded CHP has been achieved.
- The operating conditions and efficiency of an energy system have been **quantified**.
- By coupling the networks it is possible to begin exploring the optimal integration of the systems (common welfare).

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Q&A session

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Thanks for you attention!

Any questions regarding the presentation?

References

[1] Oxford English Dictionary, *Interdependency*. [Online]. Available: www.oed.com [Accessed: Aug. 26, 2007].

[2] Rinaldi, S.M., J.P. Peerenboom, and T.K.Kelly, “Identifying, understanding and analyzing critical infrastructure interdependencies,” *IEEE Control Systems Magazine*, vol. 21, issue 6, pp. 11-25, December 2001.

[3] Osiadacz, A.J., *Simulation and Analysis of Gas Networks*, 1st edition, UK: E. & F. N., 1987.

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[5] Brameller, A. and Hamam, Y.A., *The Application of Newton-Raphson Technique to Gas Network Analysis*, AGA, Fifth Winter Workshop, 1970.