Benchmark gas distribution network for cross-sectoral applications

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***Abstract*— Cross-sectoral coupling of energy systems could provide the necessary flexibility for future energy systems with a high share of renewable energies. The gas grid implies large storage capacities and thus promises an economically attractive balance for fluctuating energy sources. A benchmark gas distribution network, coupled to the CIGRE benchmark network for electricity is presented within this paper, to universally investigate the impacts on gas grid infrastructure. The network includes interconnected meshed and radial topologies for both low and medium pressure gas networks. They have been synthesized from existing real networks in cooperation with the Rheinische NETZGesellschaft mbH. Applications range from analyzing network impacts of widespread CHP or fuel cell implementation, over comparing the cost-effectiveness of different future pathways between expansion and decommissioning of the gas grid network, to analyzing the impacts of distributed injection of renewable gas. The overall aim is to build a complete network benchmark for an integral cross-sectoral energy system including also heat.**

1 INTRODUCTION

On the way to reaching climate targets defined in Conference of the parties (COP) 21 in Paris, 2015, integrating renewable energies into the current energy system is a central challenge. Fluctuation of energy from wind and sun, as well as seasonal gaps in energy provisioning need to be balanced. Therefore seasonal storage capacities are necessary which can be found in the gas grid. The research project ES-FLEX-INFRA aims at developing a software prototype to help energy and service providers optimizing technologies to interconnect the sectors electricity, gas and heat. [1] The grid infrastructure has limiting constraints which need a thorough assessment. To analyze the impacts of coupling the different sectors on the infrastructure, benchmark networks are generally accepted. As they are synthesized and fully documented, they tend to have a general validity with verifiable results.

In 2013, the “conseil international des grands réseaux électriques” (CIGRE) published several benchmark systems to analyze the "network integration of renewable and distributed energy resources" for electricity. [2] It is used as a basis to develop a benchmark gas distribution network which is presented in this paper.

2 METHODOLOGY AND ASSUMPTIONS

For this benchmark network, the gas distribution grid of the network operator Rheinische NETZGesellschaft mbH (RNG), which covers the area of Cologne and surroundings, is analyzed. It consists of a high pressure ring feeding interconnected medium (MP) and low pressure (LP) networks. As this network historically grew over several decades, very heterogeneous topologies are found. Six different ones for each LP and MP network have been used as references for meshed as well as for radiation networks. The following characteristics have been extracted to be constituted into the reference network:

- pipe diameters, materials and lengths,
- building structure and usage within the analyzed topologies,
- longest pipe length from the superordinate network transmission node to the client.

The gas composition was chosen in reference to standard parameters from DVGW (German Technical and Scientific Association for Gas and Water) worksheet G 260 which prescribes the gas quality requirements for Germany. [3] The input gas is a low calorific gas (L-gas) typical for Germany, with a calorific value of 9.8 kWh/m³ and a Wobbe-Index (WI) of 12.4 kWh/m³. It has a relative density of 0.626. The prescribed quality requirements for L-gas are resumed in Table 1.

Table 1: gas quality requirements for L-gas

calorific value [kWh/m³]	**8.4 - 13.1**
Wobbe index [kWh/m³]	11 - 13
relative density [1]	0.55 - 0.75

3 BENCHMARK GAS DISTRIBUTION NETWORK

Unlike in the electricity sector, where medium and low voltage have separate tasks, MP and LP in the gas network both are used to distribute gas to households and are not galvanically isolated. The CIGRE MV benchmark network was chosen to be used as a basis underlying network to build the gas distribution network upon.

3.1 Structure of the distribution network

The distribution network presented, consists of an MP and an LP area which are interconnected. They are fed by a superordinate high pressure grid, operating at 12 bar and feeding also the MP connection to a facility of industry or trade. The network diagram of the grid is shown in Figure 1. MP is fed with gas at 700 mbar and LP at 50 mbar. The minimum supply pressure is 280 mbar for the MP network and 26 mbar for the LP network. Each household is connected via a pressure regulator which relaxes the pressure to 22 mbar. These regulators are neglected in this work.

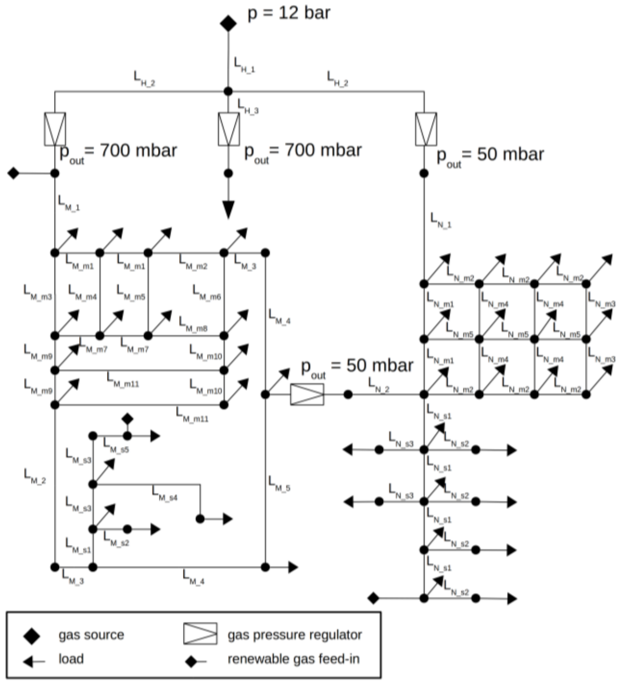

Figure 1: gas distribution network diagram

All pipes are marked as the variable L and referenced in Table 2. The roughness was chosen according to [4]. The network has been built in the simulator MYNTS®, developed by Fraunhofer SCAI. [5] In total it comprises 110 pipes, 4 regulators including heaters, 110 nodes incl. 42 demand nodes, one main gas source and three gas feed-in nodes. The four regulators are pressure-regulated and the heaters are inactive by default, as the minimum temperature simulated at the regulator output is 3.8 °C.

Table 2: pipe parameters

name	material	length l [m]	diameter d [mm]	roughness k_i [mm]
L_{N1}	steel	850	180	1
L_{N2}	steel	1050	180	1
L_{Nm1}	steel	100	180	1
L_{Nm2}	steel	250	150	1
L_{Nm3}	steel	100	150	1
L_{Nm4}	PE80SDR17.0	100	125	0.2
L_{Nm5}	PE80SDR11,0	250	110	0.2
L_{Ns1}	steel	120	180	0.2
L_{Ns2}	PE80SDR17,0	70	63	0.1
L_{Ns3}	steel	70	80	0.2
L_{M1}	steel	1200	300	0.2
L_{M2}	steel	700	150	0.2
L_{M3}	steel	100	150	0.2
L_{M4}	steel	300	150	0.2
L_{M5}	steel	700	150	0.2
L_{Mm1}	steel	75	160	1
L_{Mm2}	steel	300	160	1
L_{Mm3}	PE100SDR17.0	160	150	0.2
L_{Mm4}	PE100SDR11.0	150	63	0.2
L_{Mm5}	PE80SDR11.0	150	125	0.2
L_{Mm6}	steel	150	100	1
L_{Mm7}	PE100SDR17.0	75	90	0.2
L_{Mm8}	steel	150	80	1
L_{Mm9}	steel	75	150	1
L_{Mm10}	steel	75	50	1
L_{Mm11}	steel	300	50	1
L_{Ms1}	steel	200	100	0.2
L_{Ms2}	steel	80	80	0.2
L_{Ms3}	PE100SDR17.0	200	90	0.1
L_{Ms4}	PE100SDR17.0	700	90	0.1
L_{Ms5}	PE100SDR11.0	120	63	0.1
L_{H1}	steel	1000	400	0.2
L_{H2}	steel	1000	300	0.2
L_{H3}	steel	500	300	0.2

3.2 Loads in the network

Loads have also been synthesized in reference to the building structure, number of households and industry or businesses in the referenced networks. A connection rate of 70 % to the gas network was assumed for the inhabitant structure which was derived from the referenced networks and which is slightly higher as the overall connection rate of 60 % over all Germany. [6] Figure 2 gives an overview over all loads in the grid and Table 3 contains the values for the static maximum demand assigned to them.

A simultaneity factor of 0.7 is included in these maximum loads which are mainly based on the household structure. The loads marked in grey are linked to the CIGRE network. Details are described in 3.3.

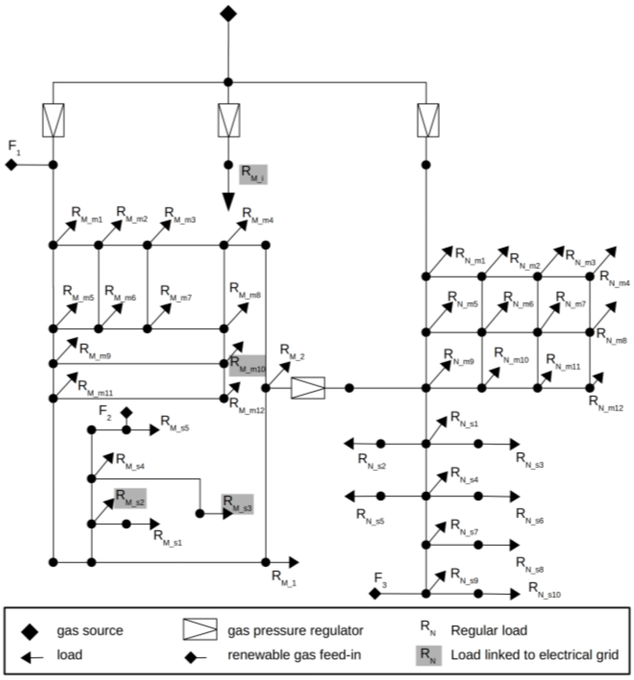

Figure 2: Loads in the benchmark network

Load R_{M_2} accounts for a compressed natural gas (CNG) service station. It is designed to be able to refuel up to 80 cars per day and equipped with a compressor, forwarding the gas with 280 bar into a high pressure storage, from which it is expanded into the storages of the cars. [7]

Table 3: Loads assigned in the grid

Load #	power [MW]	Load #	power [MW]
R_{M_m1}	0.2787	**R_{N_m1}**	0.0735
R_{M_m2}	0.5574	**R_{N_m2}**	0.1470
R_{M_m3}	0.3546	**R_{N_m3}**	0.1470
R_{M_m4}	0.0760	**R_{N_m4}**	0.0735
R_{M_m5}	0.3693	**R_{N_m5}**	0.1470
R_{M_m6}	0.5574	**R_{N_m6}**	0.2940
R_{M_m7}	0.3546	**R_{N_m7}**	0.2940
R_{M_m8}	0.1666	**R_{N_m8}**	0.1470
R_{M_m9}	0.1813	**R_{N_m9}**	0.0735
R_{M_m10}	0.6523	**R_{N_m10}**	0.1470
R_{M_m11}	0.0907	**R_{N_m11}**	0.1470
R_{M_m12}	0.0907	**R_{N_m12}**	0.0735
R_{M_s1}	0.2646	**R_{N_s1}**	0.0368
R_{M_s2}	0.2736	**R_{N_s2}**	0.2352
R_{M_s3}	0.5131	**R_{N_s3}**	0.0510
R_{M_s4}	0.6762	**R_{N_s4}**	0.0368
R_{M_s5}	0.2646	**R_{N_s5}**	0.2352
R_{M_1}	0.3500	**R_{N_s6}**	0.0510
R_{M_2}	0.9000	**R_{N_s7}**	0.0368
R_{M_i}	1.2210	**R_{N_s8}**	0.0510
		R_{N_s9}	0.0368
		R_{N_s10}	0.2080

Load profiles can be generated from the static loads, using the routines for standard gas load profiles developed by TU Munich and the full load hours indicated by BDEW for different types of consumers. [8]

3.3 *Links to the CIGRE medium voltage benchmark network*

The CIGRE benchmark network already includes two types of connections to the gas grid: combined heat and power (CHP) units and fuel cells. Although the fuel cells were meant to be run with hydrogen, nowadays fuel cells that run on natural gas are more common. It is thus assumed that these fuel cells are run on natural gas. Similarly, the CHP was meant to be driven on diesel which also was changed to a gas-driven one. Table 4 gives an overview over the implemented linked loads. [9, 10] It indicates the electrical η_{el}, as well the overall efficiency η_{tot} – both systems combine heat and power. Their power output is included as one part of the loads in Table 3.

Table 4: Loads linked to the electrical network

Part of load #	Type	Power [MW]	Eff. η_{el} [1]	Eff. η_{tot} [1]
R_{M_i}	Cogeneration plant	0.7210	0.43	0.86
R_{M_m10}	Fuel cell	0.4710	0.45	0.85
R_{M_s2}	Fuel cell	0.0825	0.4	0.9
R_{M_s3}	Fuel cell	0.0280	0.5	0.9

As these connections only consider the conversion of gas to power, additional (optional) links of power to gas are implemented in this network. They can be implemented at the renewable gas feed-in. The following two technologies with an output power of both 1 MW are suggested: an electrolyzer with an overall efficiency of 70 % and a methanation plant with an efficiency of 58 % both from electrical energy to gas. [11] The impacts of this feed-in are summed up in the following chapter.

3.4 *Feed-in of renewable gas*

Requirements to the feed-in of renewable gas are defined in the DVGW worksheet G 262. [12] Renewable gas includes bio-methane (from biogas or sewer gas), hydrogen from renewable electrical energy and synthetical methane made from renewable hydrogen. The benchmark network, as shown in Figure 2, comprises three feed-in points: F_3 within the LP network as well as F_1 and F_2 within the MP network.

3.4.1 *Biogas*

Feeding-in bio-methane is already state-of-the-art, although not common yet, as biogas is foremost used directly in CHP units. To meet the quality standards, biogas has to be desulphurized, dehydrated, cleaned from CO_2, conditioned and compressed before feeding it into the grid. [13] After this processing, it contains around 96 Mol-% methane. Typical gas qualities of bio-methane are a calorific value of 10.6 kWh/m^3, a WI of 13.9 kWh/m^3 [6] and a relative density of 0.5877.

3.4.2 *Hydrogen*

Hydrogen, which is used to constitute up to 50 % of the city gas in the past, is almost completely driven out of the current gas mix. It has a WI of 13.43 kWh/m^3, a calorific value of 3.54 kWh/m^3 and a relative density of 0.07

compared to air. As it was such a substantial part in the past, it is assumed that the grid is designed to withstand up to 50 % of hydrogen. [6] Susceptible to hydrogen are other parts of the infrastructure, such as storage tanks (esp. those of CNG cars) and gas turbines. Grids with CNG service stations are thus limited to a maximum of 2 % hydrogen in the gas mix. Hydrogen in the gas mix increases the flow velocity and thus accounts for higher pressure losses. More power is needed to compress the gas which can be neglected in the present network. [6] At the inlet of hydrogen the temperature slightly drops which is more relevant at higher pressures. The relative density decreases and in turn the WI. Thus it can be used in exchange of nitrogen. [14] On the other hand, the feed-in point has to be chosen in a way that the gas mix stays predictable for the customers.

3.5 Storage

The options for storage of gas in the distribution network are decreasing, as most of them are not profitable any more. In this network, they are not explicitly implemented. It is assumed that the feed-in plants, as well as the CNG service station have storages at their disposal. Further “stand-alone” options have yet to be evaluated.

4 SCOPE OF APPLICATIONS

The advantage of benchmark networks is their general viability and comparability. This rather simple distribution network can be used to simulate the effects of sector-coupling technologies onto the gas grid. While CHP and fuel cell technologies can be regarded as another load in the grid, the feed-in of hydrogen or bio-/synthetical-methane combined with the consideration of dynamical load profiles is a more complex problem which needs to be further analyzed. In addition, the network can be used for exemplary profitability studies. As the demand for gas decreases and will further decrease due to progresses in efficiency and the wider use of heat pumps, it has to be evaluated, if the current gas network in its whole extension is still necessary and economically reasonable.

5 SIMULATION

MYNTS is a multi-physics network simulator which implements linear Kirchhoff equations as a backbone and is also capable of solving and optimizing non-linear problems (for gas and/or electrical and/or heat simulation). It includes models for all relevant elements of the gas network including compressors, calculates several gas laws, simulates control logics of compressors and regulators and is capable to calculate the gas composition with its molar components and properties as well as its temperature including propagation over the network and the Joule-Thomson effect. [5]

A first simulation, which is shown in Figure 3, illustrates the pressure-drop in the low-pressure network. No additional feed-in of renewable gas is active. It is obvious that the network is far from being critical, as the gauge pressure drops at minimum to 48 mbar from 50 mbar input pressure.

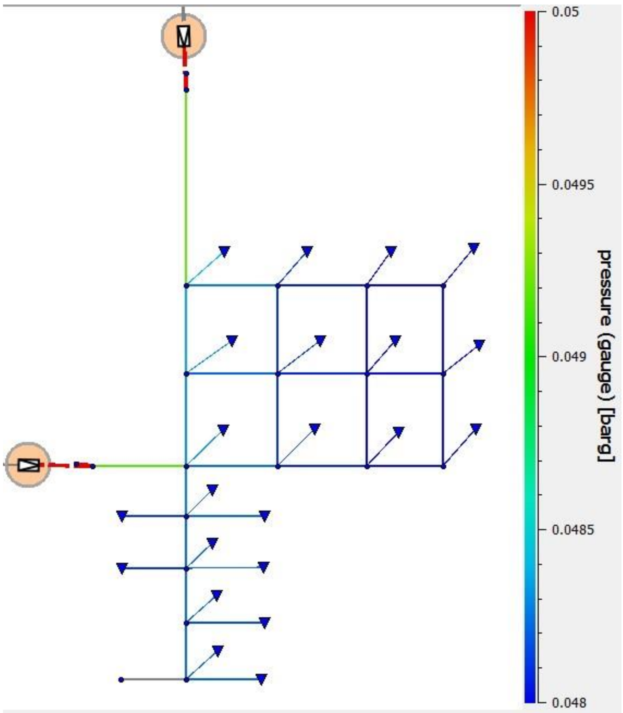

Figure 3: pressure drop in the LP network

Also in the MP network, the pressure drop is uncritical and in the worst case drops from 700 to 677 mbar gauge pressure. This clarifies again that coupling technologies from gas to power, such as fuel cells or CHP, won’t have critical effects on the gas network in general which also in reality is slightly oversized.

6 CONCLUSION AND OUTLOOK

A benchmark gas distribution network has been developed and presented in this paper. It is linked to the CIGRE MV benchmark network by natural gas fuel cells, a CHP and three optional renewable gas feed-in-nodes. As it is synthesized from real networks from RNG based in Cologne, it has a general viability for the area and produces comparable results. With its simplicity, it is suited to analyze the effects of sector-coupling technologies. A first simulation reveals that additional loads in the network won’t lead to critical conditions. The gas demand, which most likely will decrease in future, emphasizes this.

Future applications of the network will be the investigation of different gas feed-ins, as well as exemplary profitability studies to work out the future reasonability of parts of the gas network in concurrence to the electrical network.

Overall, an integral benchmark network for electricity, gas and heat is aimed at.

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The project ES-FLEX-INFRA is financed by the European Regional Development Fund (EFRE).