Modeling and simulation of coupled gas and power networks

Joint work with T. Mühlpfordt, T. Faulwasser, S. Göttlich and O. Kolb

Simone Göttlich and Eike Fokken

University of Mannheim

2nd of March 2021

Motivation

$\Longrightarrow$

Challenges of transition to renewable energy are especially

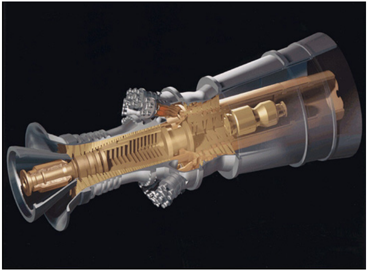
- the storage of energy
- fast reaction to demand peaks

[1] Power plant: *https://pixabay.com/photos/romania-power-plant-electricity-2765289/*

[2] Wind turbine: *https://www.pexels.com/photo/agriculture-alternative-energy-clouds-countryside-414837/*

Motivation

- Gas power plants react fast
- Potential for conjunction with Power-to-Gas plants as long term energy storage



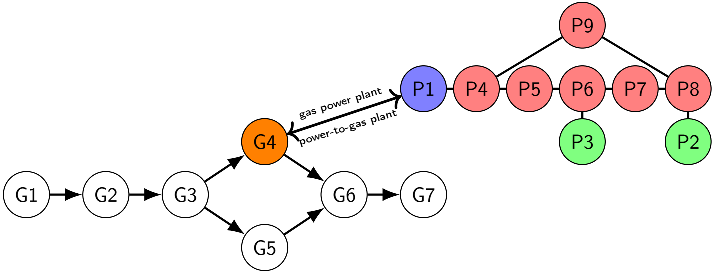
Gas turbine

[3] Gas turbine: https://commons.wikimedia.org/wiki/File:GE_H_series_Gas_Turbine.jpg

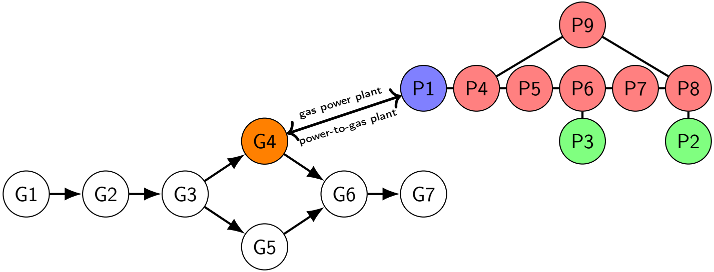
Overview

Overview

Brief model review

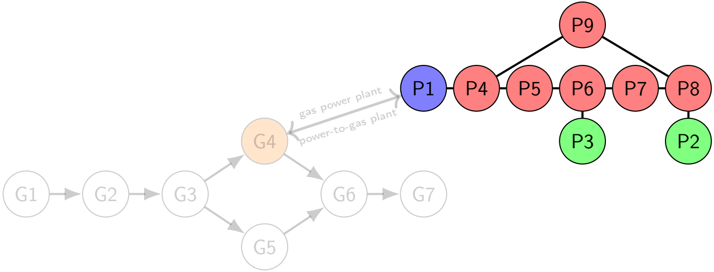


Brief model review



- network is modeled as a directed graph
- edges $\hat{=}$ different components (pipelines, compressors, ...)
  $\rightarrow$ algebraic equations, PDEs
- nodes $\hat{=}$ junctions
  $\rightarrow$ boundary conditions - e.g. demand of a load
  $\rightarrow$ coupling conditions - e.g. Kirchhoff laws, mass conservation)

Power model



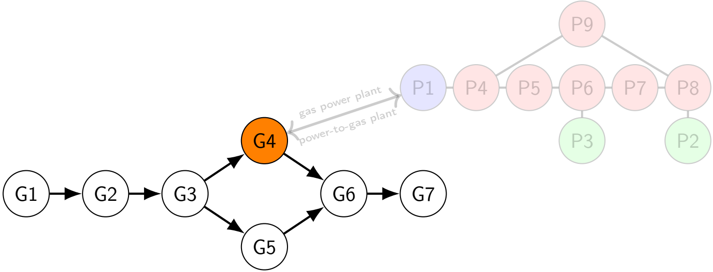
- **AC Powerflow Equations** (Parameters G_{kj}, B_{kj}):

$$P_k = \sum_{j \in \text{nodes}} \left|V_k\right|\left|V_j\right| \left[G_{kj}\cos(\phi_k - \phi_j) + B_{kj}\sin(\phi_k - \phi_j)\right]$$

$$Q_k = \sum_{j \in \text{nodes}} \left|V_k\right|\left|V_j\right| \left[G_{kj}\sin(\phi_k - \phi_j) - B_{kj}\cos(\phi_k - \phi_j)\right]$$

- PQ-/loads, PV-/generators, Vϕ/Slack Bus

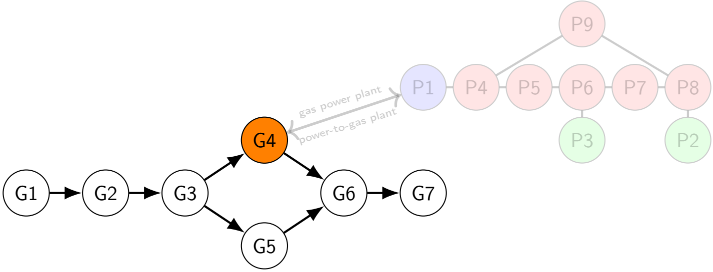
Gas model



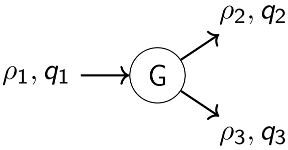
- Dynamics in every pipe: **isentropic Euler equations**
  - mass balance: $\partial_t \rho + \partial_x q = 0$
  - flow balance: $\partial_t q + \partial_x \left(p(\rho) + q^2/\rho \right) = -\lambda(q/\rho) \dfrac{q|q|}{2D\rho}$
  - well-posed[4] isothermal pressure law with z-factor: $p(\rho) = \frac{a\rho}{1+b\rho}$

[4] F. et al., Modeling and simulation of sector-coupled networks: A gas-power benchmark, In: Mathematical MSO for Power Engineering and Management(2021)

Gas model

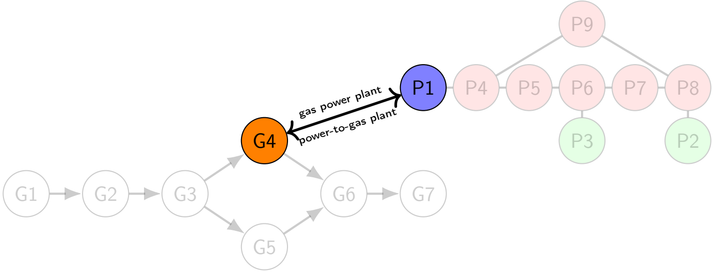


- conservation of mass and equality of pressure as coupling conditions:



$$p(\rho_1(t)) = p(\rho_2(t)) = p(\rho_3(t))$$
$$q_1(t) = q_2(t) + q_3(t)$$

Coupling of gas and power



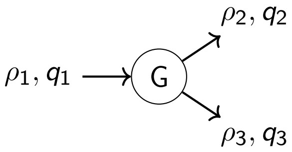
- Gas consumption depends linearly on the real power demand $P(t)$: $q(P(t)) = T_{\text{GtP}} \cdot P(t)$
- Power consumption depends linearly on the gas demand $q(t)$: $P(q(t)) = T_{\text{PtG}} \cdot q(t)$
- $T_{\text{GtP}}/T_{\text{PtG}}$: efficiency of the respective plant

Overview

Bernoulli coupling

Pressure coupling:

$$p(\rho_1) \quad = p(\rho_2) \quad = p(\rho_3)$$
$$q_1 = q_2 + q_3$$

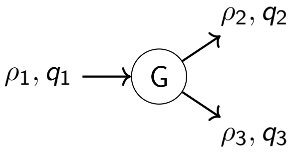


[5] Reigstad, Existence and Uniqueness of Solutions to the Generalized Riemann Problem for Isentropic Flow., SIAM J. Appl. Math. 75 (2015), no. 2

Bernoulli coupling

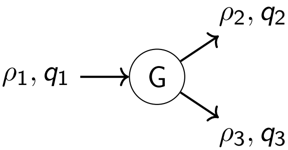
Pressure coupling:

$$H(\rho_1, q_1) = H(\rho_2, q_2) = H(\rho_3, q_3)$$
$$q_1 = q_2 + q_3$$
$$H_p(\rho, q) = p(\rho)$$



[5] Reigstad, Existence and Uniqueness of Solutions to the Generalized Riemann Problem for Isentropic Flow., SIAM J. Appl. Math. 75 (2015), no. 2

Bernoulli coupling



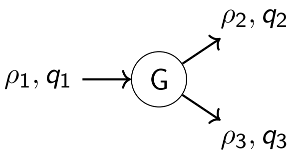
Pressure coupling:

$$H(\rho_1, q_1) = H(\rho_2, q_2) = H(\rho_3, q_3)$$
$$q_1 = q_2 + q_3$$
$$H_p(\rho, q) = p(\rho)$$

Unphysical: Bernoulli equation demands lower pressure for faster flow.

[5] Reigstad, Existence and Uniqueness of Solutions to the Generalized Riemann Problem for Isentropic Flow., SIAM J. Appl. Math. 75 (2015), no. 2

Bernoulli coupling



Pressure coupling:

$$H(\rho_1, q_1) = H(\rho_2, q_2) = H(\rho_3, q_3)$$
$$q_1 = q_2 + q_3$$
$$H_p(\rho, q) = p(\rho)$$

Unphysical: Bernoulli equation demands lower pressure for faster flow.

Bernoulli coupling[5]:

$$H_B(\rho, q) = \frac{1}{2}v^2 + \int \frac{p'(\hat{\rho})}{\hat{\rho}}\,\mathrm{d}\hat{\rho}$$

Equivalent to H_p, except for $\frac{1}{2}v^2$, but respects Bernoulli equation.

[5] Reigstad, Existence and Uniqueness of Solutions to the Generalized Riemann Problem for Isentropic Flow., SIAM J. Appl. Math. 75 (2015), no. 2

Discretization

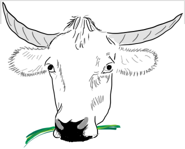
- Powerflow problem is solved for every time step.
- Discretization of the isentropic Euler equations $y_t + f(y)_x = g(y)$ is done via an implicit box scheme[6]:

$$\frac{Y_{j-1}^{n+1} + Y_j^{n+1}}{2} = \frac{Y_{j-1}^{n} + Y_j^{n}}{2} - \frac{\Delta t}{\Delta x}\left(f(Y_j^{n+1}) - f(Y_{j-1}^{n+1})\right) + \frac{\Delta t}{2}\left(g(Y_{j-1}^{n+1}) + g(Y_j^{n+1})\right)$$

  where $Y_j^n \approx y$ is the cell average.
- Scheme is only linear but is not constrained by the CFL condition $\Rightarrow$ big time steps.

[6] Bales, Kolb, Lang, *An implicit box scheme for subsonic compressible flow with dissipative source term*, Numer. Algorithms 53(2), S.293-307 (2010)

Software



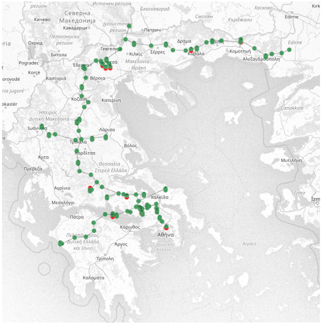
Grazer will be an open source tool for solving power-grid and gas-network simulation problems with the following properties:

- Software tests
- full standard compliance (C++17) and compiler support for GCC, Clang, MSVC.
- free software: GNU Affero General Public License 3.0

Grazer will be released in the summer of 2021.

Overview

Realistically sized gas network



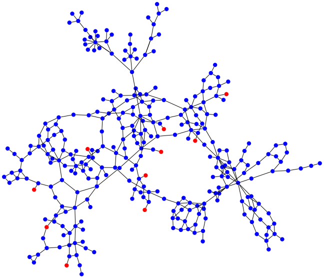
Gaslib-134, approximation of a greek gas network

Gaslib-134[7]:

- 86 pipelines
- 3 inflow nodes
- 45 outflow nodes
- Usual pressure range: 20 – 100bar
- pipeline length: 0.5 – 80km

[7] Schmidt et al., GasLib – A Library of Gas Network Instances, Data 2(4), Art. 40 (2017)

Benchmark power network



ieee-300 benchmark network

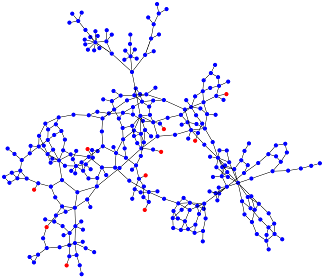
ieee-300[8]:

- 69 generator nodes
- 231 load nodes
- 411 transmission lines
- order of magnitude of national high power networks

[8] Zimmerman, Murillo-Sánchez, Thomas, MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education, IEEE Transactions Power Systems (2011)

Created with `https://immersive.erc.monash.edu/stac/`

Benchmark power network



ieee-300 benchmark network

ieee-300[8]:

- 69 generator nodes
- 231 load nodes
- 411 transmission lines
- order of magnitude of national high power networks

Coupling:

- 10 gas-power conversion plants

[8] Zimmerman, Murillo-Sánchez, Thomas, MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education, IEEE Transactions Power Systems (2011)

Created with https://immersive.erc.monash.edu/stac/

Gas-power conversion

We choose a constant efficiency of 40% for gas power plants:

$$P_{\mathrm{el}} = T_{\mathrm{GtP}} \cdot q$$

and one of 72% for the power-to-gas conversion[9]:

$$q = T_{\mathrm{PtG}} \cdot P_{\mathrm{el}}$$

with $T_{\mathrm{GtP}} \approx 16\,\mathrm{MJ\,kg^{-1}}$ and $T_{\mathrm{PtG}} \approx 0.017\,\mathrm{kg\,MJ^{-1}}$. This yields for the round trip *Power*⇝*Gas*⇝*Power* an efficiency of 28.8%.

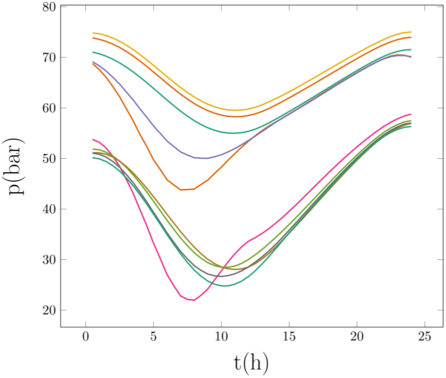
[9] Trimis et al., Potenzial der thermisch integrierten Hochtemperaturelektrolyse und Methanisierung für die Energiespeicherung durch Power-to-Gas (PtG),gfw Gas 155 (2014) ,no. 1-2

Simulation

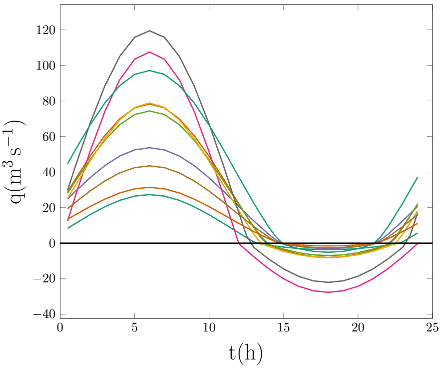
- Simulation time $T = 24\,\text{h}$ with $\Delta t = 0.5\,\text{h}$
- $\Delta x \leq 10\,\text{km}$
- 10 gas-power conversion nodes
- Power demand: $P_{\text{demand}} = P_{\text{s}} + P_{\text{v}} \sin(2\pi \frac{t}{24\text{h}})$
- Power generation in the power grid remains constant
- Surplus demand must be satisfied by gas power plants
- During low demand, excess power is converted to gas

Overview

Results: Gas-power conversion



Pressure over time.



Consumed/generated flow over time.

Results: Pressure coupling vs. Bernoulli coupling

$\max\left\lvert p_p - p_b \right\rvert$	$\max \frac{\left\lvert p_p - p_b \right\rvert}{p_p}$
$0.2\,\text{bar}$	0.004

range $[\text{kg}\,\text{s}^{-1}]$	$\max\left\lvert q_p - q_b \right\rvert$	$\max \frac{\left\lvert q_p - q_b \right\rvert}{\left\lvert q_p \right\rvert}$
$10^{-3} < \left\lvert q_p \right\rvert < 10^{-2}$	$0.0003\,\text{kg}\,\text{s}^{-1}$	0.3270
$10^{-2} < \left\lvert q_p \right\rvert < 10^{-1}$	$0.0141\,\text{kg}\,\text{s}^{-1}$	0.32670
$10^{-1} < \left\lvert q_p \right\rvert < 10^{0}$	$0.0177\,\text{kg}\,\text{s}^{-1}$	0.1105
$10^{0} < \left\lvert q_p \right\rvert < 10^{1}$	$0.0178\,\text{kg}\,\text{s}^{-1}$	0.0207
$10^{1} < \left\lvert q_p \right\rvert$	$0.0447\,\text{kg}\,\text{s}^{-1}$	0.0029

Results: Pressure coupling vs. Bernoulli coupling

$\max\lvert p_p - p_b\rvert$	$\max \frac{\lvert p_p - p_b\rvert}{p_p}$
0.2 bar	0.004

range $[\mathrm{kg\,s^{-1}}]$	$\max\lvert q_p - q_b\rvert$	$\max \frac{\lvert q_p - q_b\rvert}{\lvert q_p\rvert}$
$10^{-3} < \lvert q_p\rvert < 10^{-2}$	$0.0003\,\mathrm{kg\,s^{-1}}$	0.3270
$10^{-2} < \lvert q_p\rvert < 10^{-1}$	$0.0141\,\mathrm{kg\,s^{-1}}$	0.32670
$10^{-1} < \lvert q_p\rvert < 10^{0}$	$0.0177\,\mathrm{kg\,s^{-1}}$	0.1105
$10^{0} < \lvert q_p\rvert < 10^{1}$	$0.0178\,\mathrm{kg\,s^{-1}}$	0.0207
$10^{1} < \lvert q_p\rvert$	$0.0447\,\mathrm{kg\,s^{-1}}$	0.0029

Rather small effects

Bernoulli coupling implementation

- Bernoulli coupling condition uses the flow velocity $v = \frac{q}{A}$. Therefore we need the pipe diameter A.
- Some connections in GasLib lack all physical properties.
- $\Rightarrow$ need case-by-case coupling conditions.
- Probably the modeling errors are greater than the coupling errors.

Summary

Summary:

- Efficient simulation of large networks over a time span of days
- We have introduced a single framework for the coupling of power and gas.
- Bernoulli coupling possible, yet we saw small benefits.

Future work:

- Finalizing and publishing Grazer
- Uncertain electricity demand and repercussions on the gas net.

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

Summary

Summary:

- Efficient simulation of large networks over a time span of days
- We have introduced a single framework for the coupling of power and gas.
- Bernoulli coupling possible, yet we saw small benefits.

Future work:

- Finalizing and publishing Grazer
- Uncertain electricity demand and repercussions on the gas net.

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Thank you for your time