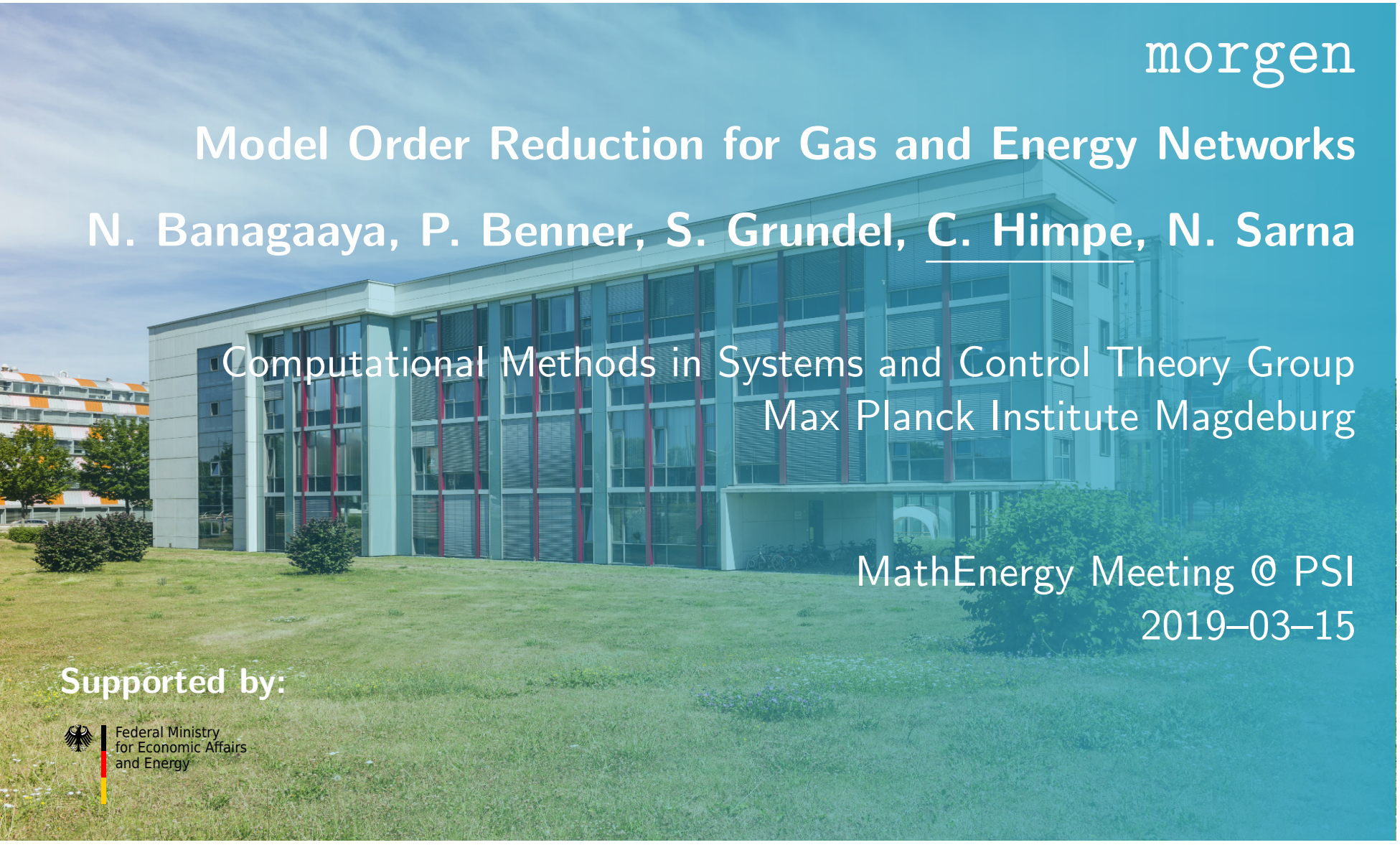


MAX PLANCK INSTITUTE
FOR DYNAMICS OF COMPLEX
TECHNICAL SYSTEMS
MAGDEBURG

CSC
COMPUTATIONAL METHODS IN
SYSTEMS AND CONTROL THEORY

morgen

Model Order Reduction for Gas and Energy Networks

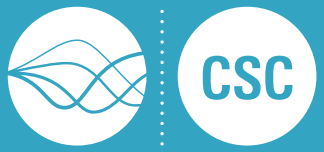
N. Banagaaya, P. Benner, S. Grundel, C. Himpe, N. Sarna

Computational Methods in Systems and Control Theory Group
Max Planck Institute Magdeburg

MathEnergy Meeting @ PSI
2019–03–15

Supported by:

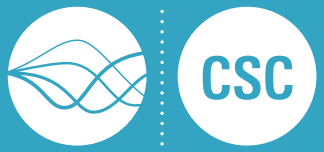
Federal Ministry
for Economic Affairs
and Energy



MathEnergy @ MPI Magdeburg

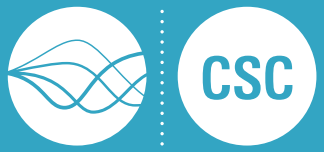
Sub-Project: **Model Order Reduction**

- Development and assessment
- of model reduction methods
- for dynamic gas network models
- to accelerate control and scenario analysis
- as part of the MathEnergy software library.



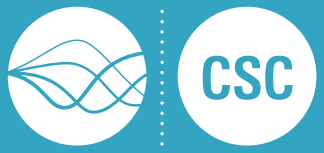
morgen

- Modular,
- extensible,
- open
- test platform
- for: model order reduction
- of: multi-dimensional network dynamics,
- for example: **Gas**, Power, Heat, Water;
- compatible with: MATLAB & OCTAVE.



Model Reduction for Gas Network Dynamics

- Model: coupled 1D isothermal Euler equations [Benner et al'18]
- Properties: nonlinear, hyperbolic, input-output
- Model Reduction: system-theoretic, data-driven [H.'18]
- Training: short generic scenarios
- Testing: long realistic scenarios [Hellwig'03]



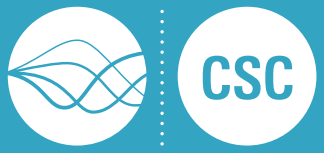
Modules

- Models
- Solvers
- Decouplers
- Reductors
- Networks

- Tests (Experiments)
- Utilities (Import, Heuristics, Visualization)
- Documentation (User, Developer, Formats, Interfaces)

Models

- **Differential-Algebraic Equation System** [In Preparation]
  - spatial end-point discretization
  - index-1 model
- **Ordinary Differential Equation System** (I) [Grundel et al'14]
  - spatial mid-point discretization
  - simple index reduction
  - visible oscillations
- **Ordinary Differential Equation System** (II) [Benner et al'18]
  - spatial end-point discretization
  - involved index reduction
  - small oscillations



Solvers

- **Linearizing Implicit Euler**
  - first order accurate
  - fixed time-steps width
  - ODE and DAE, simple implementation
- **Generic** (`ode15s`) [Shampine & Reichelt'97]
  - variable order accuracy
  - adaptive time-steps width
  - ODE and DAE, integrated in MATLAB and OCTAVE
- **Implicit-Explicit Runge Kutta** (I) [Grundel & Jansen'15]
  - first-order accurate
  - fixed time-step width
  - ODE only, very fast
- **Implicit-Explicit Runge-Kutta** (II) [Pareschi & Russo'05]
  - second-order accurate
  - fixed time-step width
  - ODE only, WIP

Decouplers

- **Quadratic** [Banagaaya et al'18]
  - ☺ resolves nonlinearity
  - ☹ assumes fixed flow direction
- **Nonlinear** [Banagaaya et al'19]
  - ☺ results comparable to analytic index reduction
  - ☺ independent from spatial discretization
  - ☺ numerically robust

Reductors

- **Structured Proper Orthogonal Decomposition** [Sirovich'87, H. et al'18]
  - ☺ simple, baseline
  - ☹ can be unstable, state-only
- **Structured Empirical Balanced Truncation** [Lall et al'99, Hahn & Edgar'02]
  - ☺ likely stable, standard
  - ☹ high complexity
- **Structured Empirical Cross Gramian** [H. & Ohlberger'14, Jiang et al'18]
  - ☺ medium complexity
  - ☹ can be unstable
- **Structured Empirical Non-Symmetric Cross Gramian** [H. & Ohlberger'16]
  - ☺ medium complexity
  - ☹ can be unstable
- **Structured Empirical Dominant Subspaces** [H. & Benner'18]
  - ☺ medium-low complexity
  - ☹ likely stable
- **Structured Dynamic Mode Decomposition-Galerkin** [Alla & Kutz'17]
  - ☺ simple, non-energetic
  - ☹ likely stable, state-only

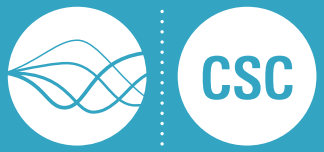
Networks

Synthetic:

- Procedural Pipeline
- MORGEN Network (WIP)
- Network from [Kiuchi'94] (WIP)
- Network from [Grundel et al'13]
- Network from [Grundel et al'14]
- Network from [Grundel et al'15]
- Network from [Mak et al'15]
- Network from [Farzaneh-Gord et al'16]
- Networks from [Grundel et al'16]
- Network from [Pambour et al'16]
- Network from [Domschke et al'17]
- Network from [Egger et al'18]
- Networks from [Sundar & Zlotnik'18]

Realistic:

- Belgian Transport Network [De Wolff & Smeers'00]
- Yamal-Europe Pipeline [Chaczykowski'09]
- Network from [Szoplik'12] (WIP)
- GasLib-40 [Schmidt et al'17] (WIP)
- GasLib-134 [Schmidt et al'17] (WIP)
- GasLib-135 [Schmidt et al'17] (WIP)
- GasLib-582 [Schmidt et al'17] (WIP)
- GasLib-4197 [Schmidt et al'17] (WIP)
- Fermaca Network [Rodriguez-Blanco'18] (WIP)

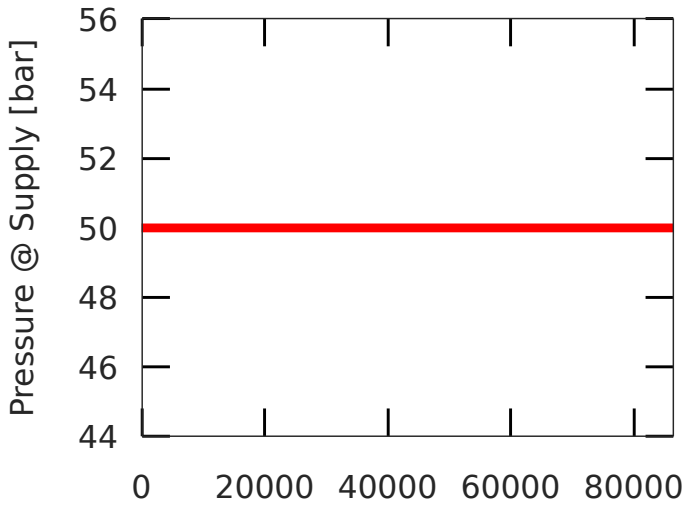


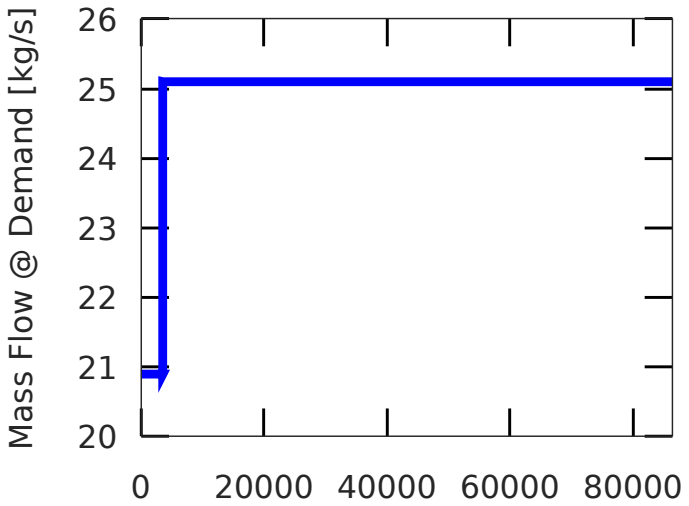
PSI Pipeline Example

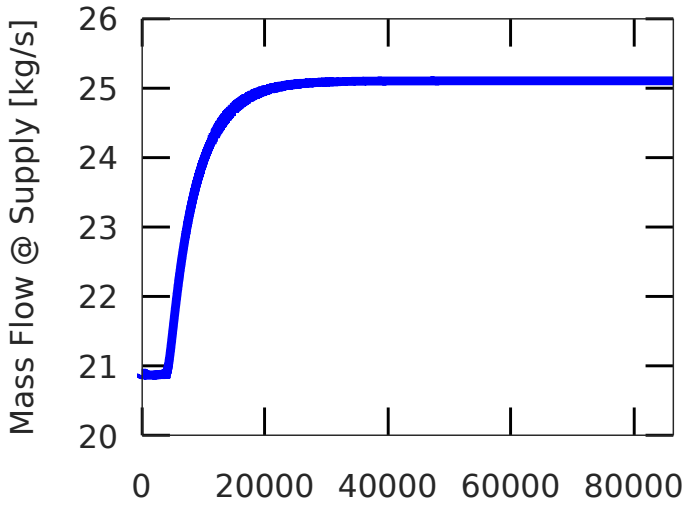
Length:	$100,000$m
Diameter:	0.5m
Roughness:	0.0001m
Temperature:	$10°$C
Pressure:	50bar
Mass-Flow:	21kg/s
Friction:	Hofer
Compressibility:	Papay
Parameter:	Temperature, specific gas constant
Training:	Impulse
State-Space:	80

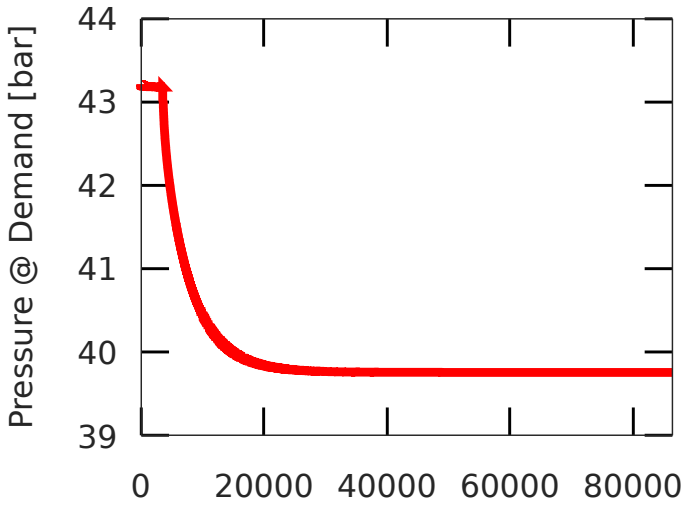
(Thank You, PSI.)

Numerical Results

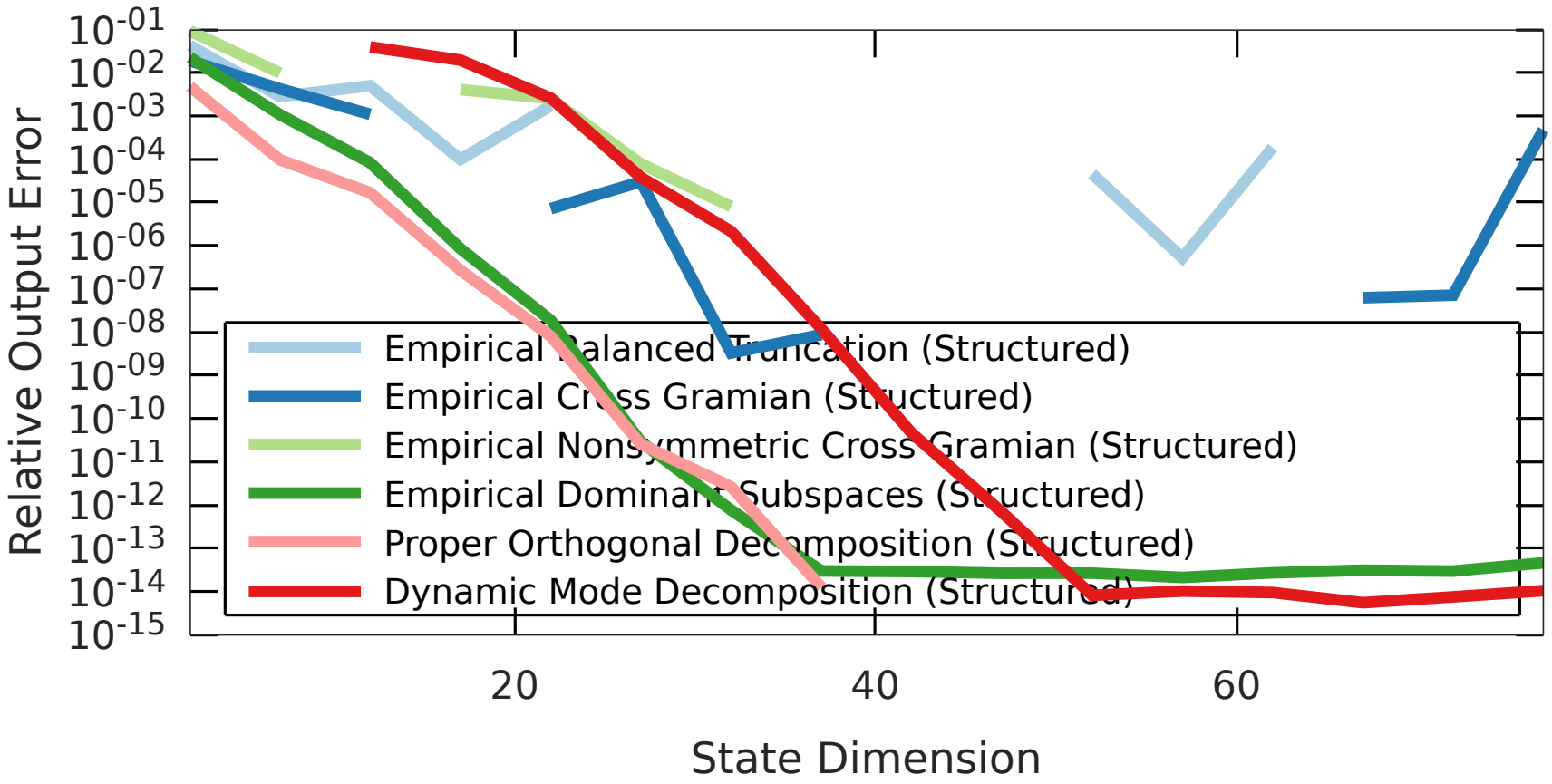




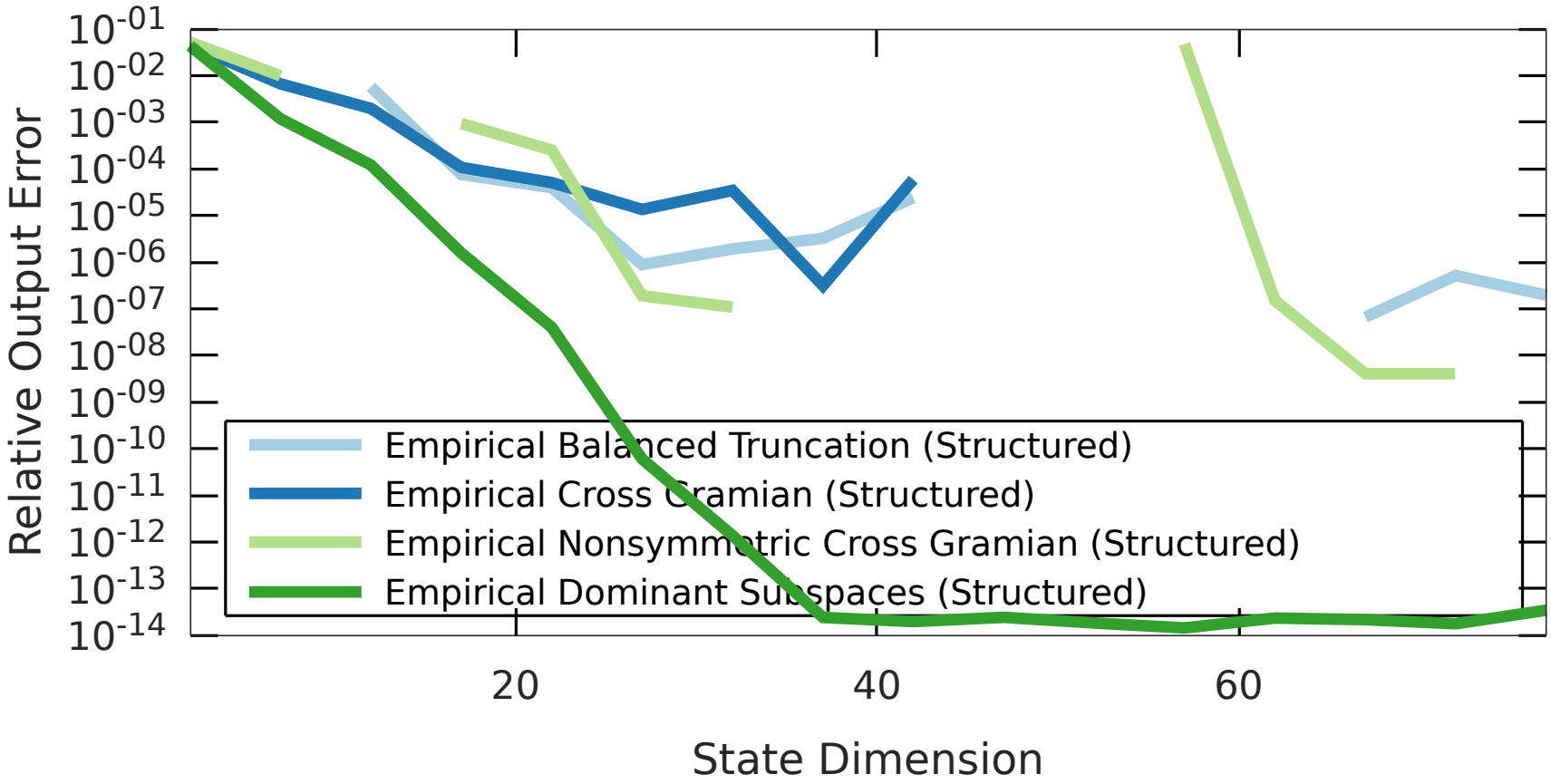




Model Reduction Error (Non-Parametric)



Model Reduction Error (Parametric)



Milestones

MS3:

AP2 All MOR methods implemented. (✓)
→ Six data-driven methods are available.

AP3 Initial scenario analysis. (✓)
→ Small networks can be analyzed.

AP5 Power-2-Gas evaluation. (✓)
→ Is buffered and time scales are different.

MS4:

AP2 Full version of software.

AP3 Full scenario analysis of demonstrator.

Outlook

- Free boundary configuration
- Improved DAE / ODE models & active elements
- Large-scale tests (GasLib, Zollverein)
- Planned (open-source) release: Q4 2019
- More model reduction methods? (i.e. Linearized, Hyperbolic, ...)

Acknowledgment:
Supported by the German Federal Ministry for Economic Affairs and Energy, in the joint project: "**MathEnergy** – Mathematical Key Technologies for Evolving Energy Grids", sub-project: Model Order Reduction (Grant number: 0324019**B**).