TECHNISCHE UNIVERSITÄT WIEN

Energy Economics Group

Designing a model for the cost-optimal decommissioning and refurbishment investment decision of gas networks

Application on a real test-bed in Austria until 2050

EEG-Seminar – Internal Presentation

Sebastian Zwickl-Bernhard

24.03.2022

Corresponding author/Presenter: zwickl@eeg.tuwien.ac.at

Todays' agenda

- Background / Motivation and core objective
- Materials and methods
- Options to test a newly developed model
- Results of a real test-bed until 2050 (Vorarlberg, Austria)
- Conclusions and outlook

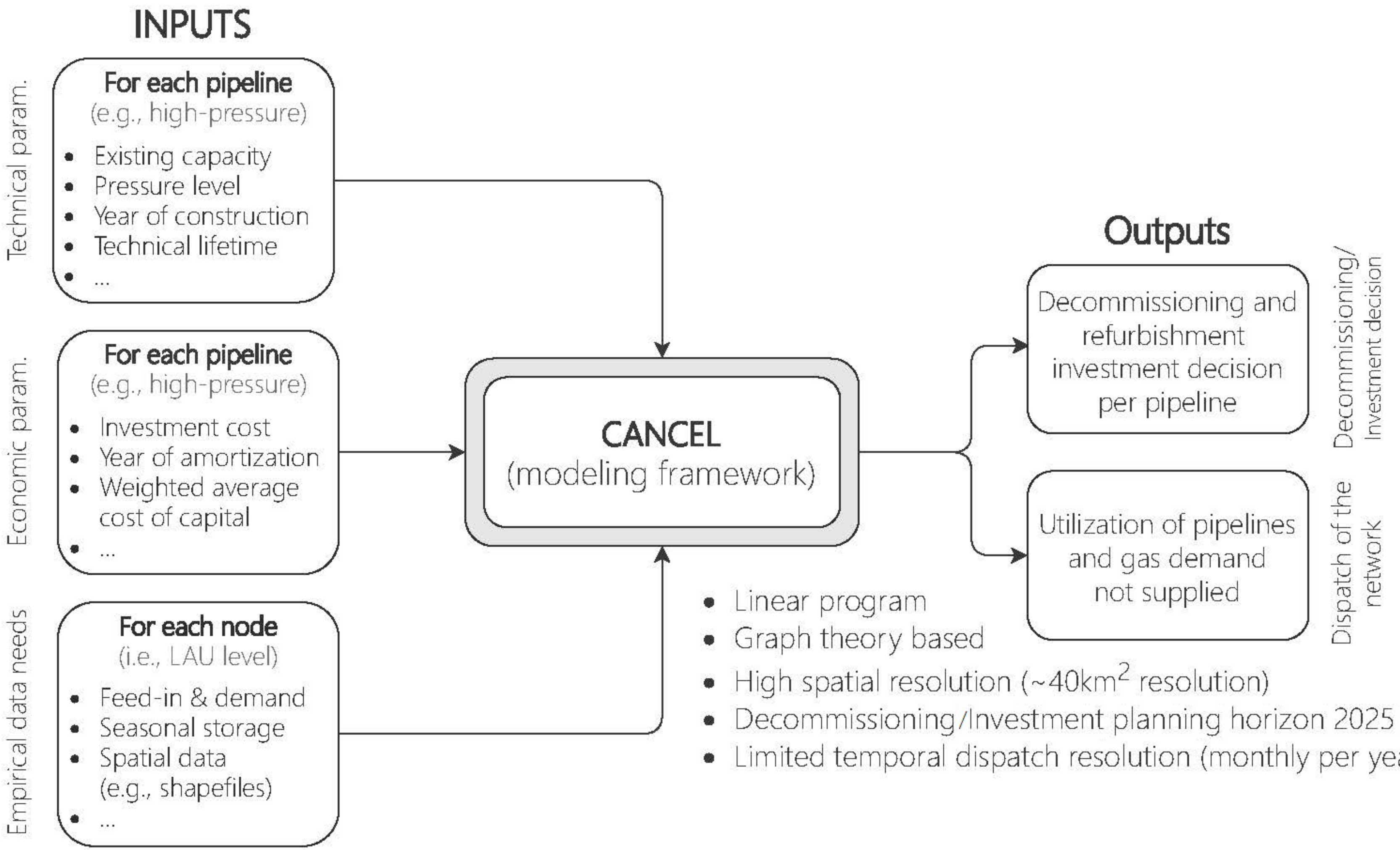
Background and motivation

- Adherence to the remaining CO_2 budget of the 1.5°C / 2.0°C climate target requires rapid **defossilization** of the energy system
- Concrete measures include, among others, the **substitution** of **natural gas** in the provision of energy services by sustainable alternatives
- Substantial **challenge** since natural gas is currently **used** for energy supply of a **wide range** of energy service needs
  - Generation of process heat or as raw material for industrial consumer
  - Centralized generation of electricity and district heating
  - Decentralized supply of space heating and hot water demands
- Uncertain role of **green gases** (e.g., synthetic gas, hydrogen) related to their economic viable quantities / potentials and penetration time
- …but there are far-reaching gas transmission / distribution networks

Core objective / main research questions

- The core objective of this work is to investigate the **cost-effective trajectory** of **gas networks** from a systemic point of view under a long-term planning horizon
- In view of necessary refurbishment investments in existing gas network infrastructure and pipelines due to their technical lifetimes, the main research question is of **which decommissioning and refurbishment investment decision result in a cost-effective gas networks by 2050.**
- Equally important in the analysis is the trade-off decision from the network operator's perspective whether available **gas demands** within the network area **are supplied or not** as the decommissioning of existing gas pipelines can be cost-effective, but at the same time results in not supplied gas demands.

Introduction into the model



- Linear program
- Graph theory based
- High spatial resolution (~40km^2 resolution)
- Decommissioning/Investment planning horizon 2025 to 2050
- Limited temporal dispatch resolution (monthly per year)

Mathematical formulation (selection) 1 / 2

Equation	Type	Short description
$\min_x Capex + Opex - Rev + Purch$	Objective function	Minimize gas network operator's net present value
$Capex = \sum_y \alpha_y * w * \Pi_y \qquad Opex = \sum_y \alpha_y * \mathrm{K}$	Constraint	Calculation of capital and operational expenditures
$\mathrm{K} = \sum_l c_l^{fix} * \Upsilon_{l,y}$	Constraint	Total fixed (operating) costs per pressure / network level $\boldsymbol{l}$
$\Pi_{p,l,y} = \Pi_{p,l,y}^{pre} + f_{p,l}^{ref} * \Pi_{p,l,y_{p,l}^{inv}}^{ref}$	Constraint	Book value of a pipeline $\boldsymbol{p}$ at $\boldsymbol{l}$ in $\boldsymbol{y}$, where $\boldsymbol{\Pi_{p,l,y}^{pre}}$ is the book value of the pre-existing pipeline (capacity)
$\Pi_{p,l,y_{p,l}^{inv}}^{ref} = c_l^{inv} * \Upsilon_{p,l,y_{p,l}^{inv}}^{ref}$	Constraint	Book value of the refurbishment investment for $\boldsymbol{p}$ and $\boldsymbol{l}$ in $\boldsymbol{y_{p,l}^{inv}}$

Mathematical formulation (selection) 2 / 2

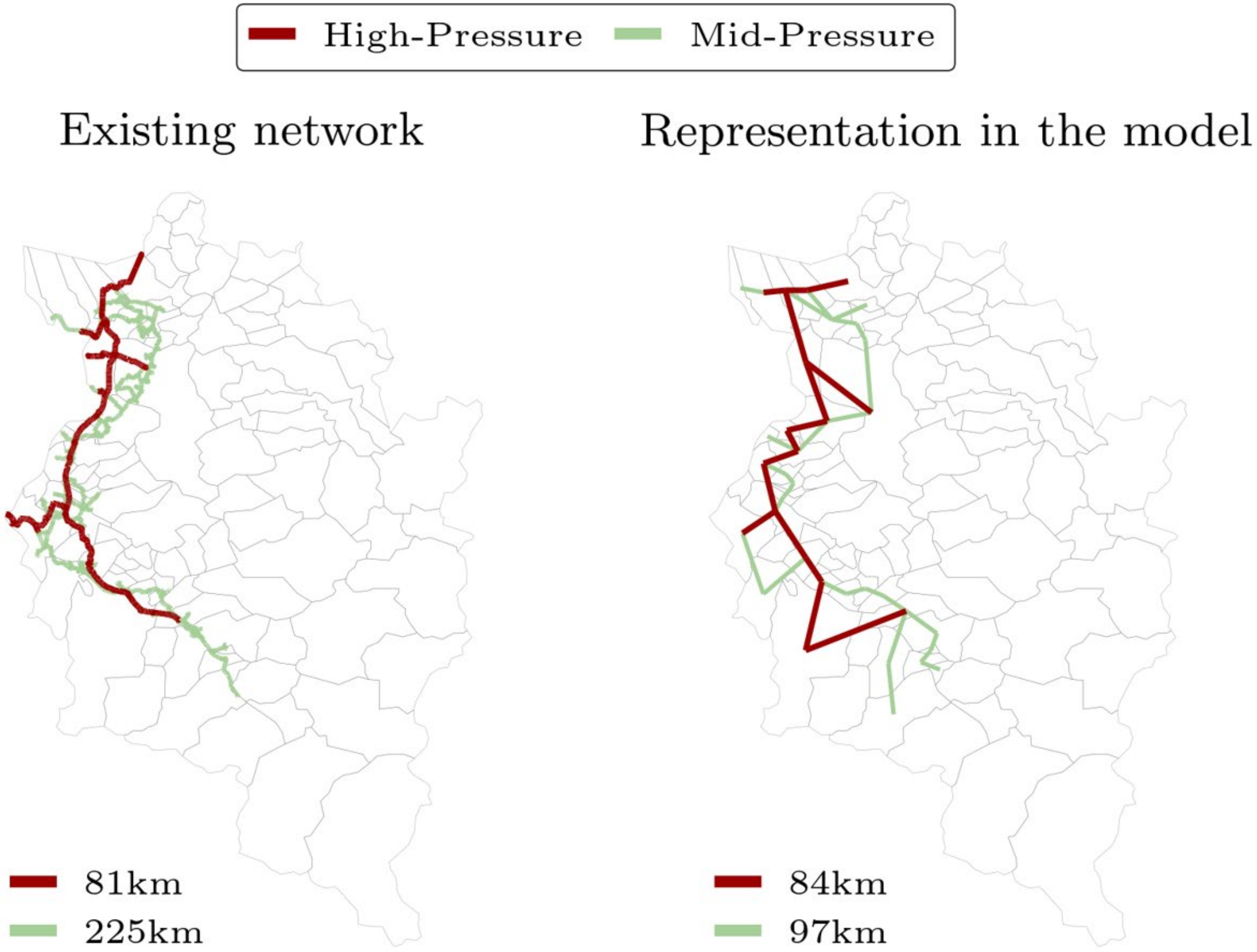
Equation	Type	Short description
$q^{fed}_{n,l,y,m} - q^{dem}_{n,ly,m} - \zeta_m * \left(q^{exp}_{n,l,y,m} - q^{imp}_{n,l,y,m}\right) + q^{sto}_{n,l,y,m} = 0$	Constraint	Nodal gas balance equation at pressure / network level
$q^{dem}_{n,l,y,m} = q^{dem,loc}_{n,l,y,m} + q^{del}_{n,l',y,m}$	Constraint	Gas demand at network level $\boldsymbol{l}$, where $\boldsymbol{q^{del}_{n,l',y,m}}$ is the amount of gas delivered to subordinate pressure level
Equation $\boxed{18}$ $\begin{cases} q^{dem,loc}_{n,l,y,m} \leq d^{max}_{n,l,y,m} & : \lambda^{co}_{n,l,y,m} \\ q^{dem,loc}_{n,l,y,m} = d^{max}_{n,l,y,m} & : \lambda^{ES}_{n,l,y,m} \end{cases}$	Constraint	Essential demand constraint and sets the upper bound of the decision variable $\boldsymbol{q^{dem,loc}_{n,l,y,m}}$
$rev = p^{loc}_{l,y} * q^{dem,loc}_{n,l,y,m}$	Constraint	Revenues created by the local gas demands covered, where $\boldsymbol{p^{loc}_{l,y}}$ is the grid usage charge at network level $\boldsymbol{l}$

Implication of demand constraint dual variables

Input			Output
Model run	Formulation of Equation $\boxed{18}$	Scenario description/gas network design (abbreviation)	Results or further used variable
1	$q^{dem}_{n,l,y,m} \leq d^{max}_{n,l,ym}$	Cost-optimal without ensured supply (CO)	Demand supplied ($\overset{*}{\mathbf{q}}{}^{dem}_{n,l,y,m}$)
2	$q^{dem}_{n,l,y,m} = \overset{*}{\mathbf{q}}{}^{dem}_{n,l,y,m}$		Shadow price ($\lambda^{CO}_{n,l,y,m}$)
3	$q^{dem}_{n,l,y,m} = d^{max}_{n,l,ym}$	Cost-optimal with ensured supply (ES)	Shadow price ($\lambda^{ES}_{n,l,y,m}$)

Table 1: Model runs and associated formulation of the gas demand constraint (Equation $\boxed{18}$), scenarios, and results or further used variables.

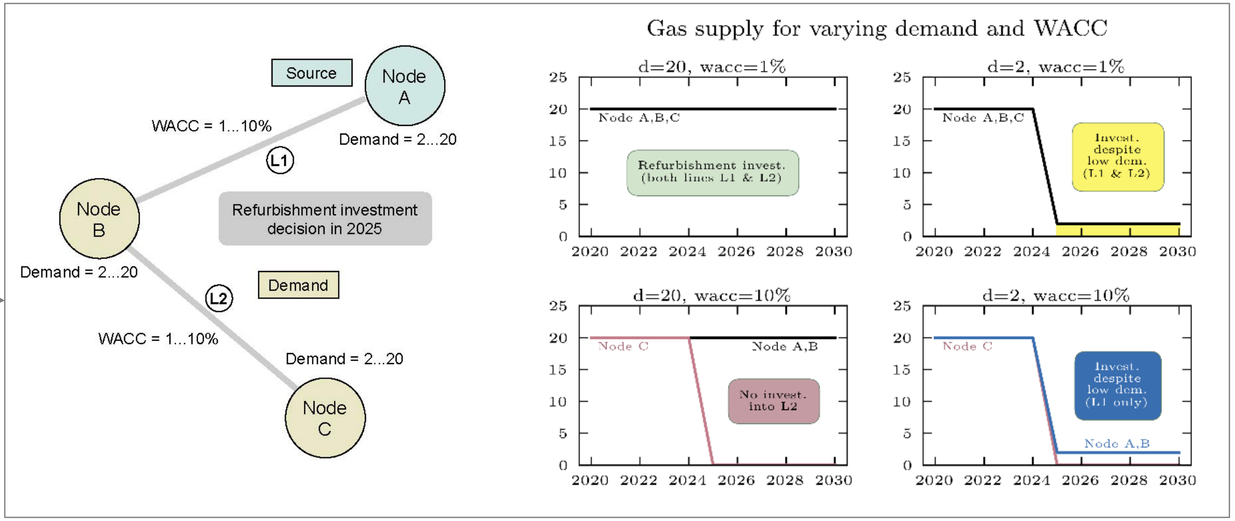
Test-bed in Vorarlberg, Austria

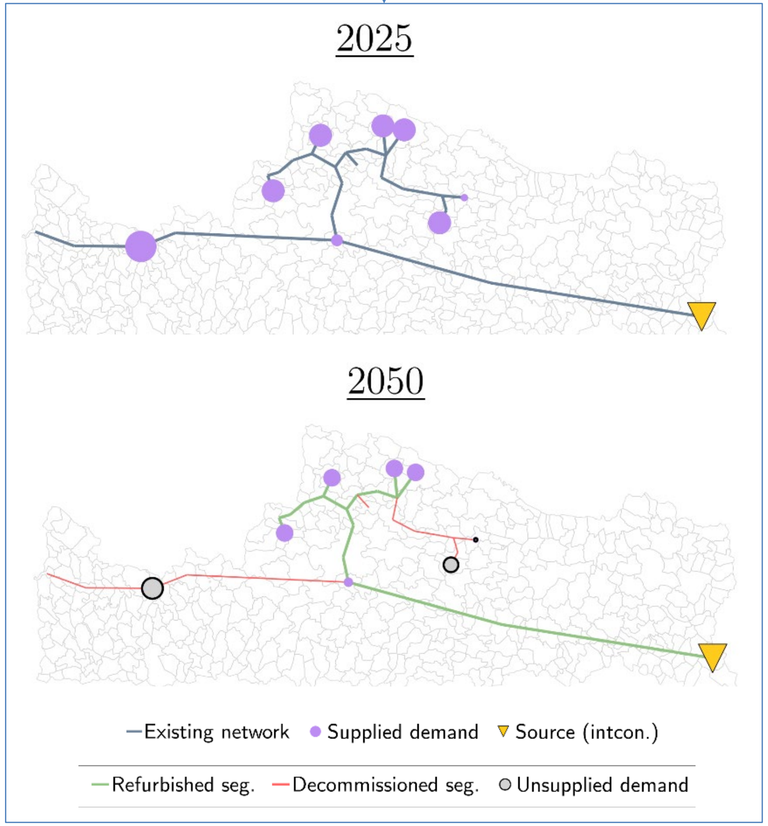


Source [57]: Vorarlberg Netz, Das Erdgasnetz: Allgemeines zum Erdgas-Verteilnetz, https://www.vorarlbergnetz.at/erdgasnetz.htm

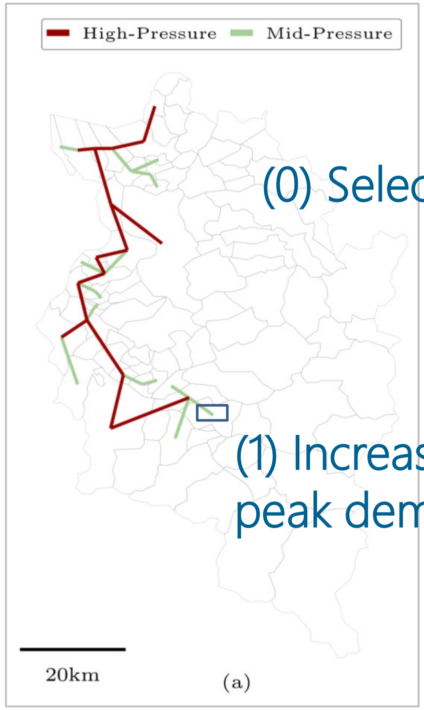
How to verify / test a newly developed model?

1. Small case example (e.g., three nodes, two lines)
2. Design illustrative (small) case study
3. Study dual variables / shadow prices





Informative value of dual variables / shadow prices



(0) Select constraint

(1) Increased peak demand

$$q_{n,l,y,m}^{dem,loc} = d_{n,l,y,m}^{max} \; : \; \lambda_{n,l,y,m}^{ES}$$

(2) Shadow price

(3) Implication (demand profile)

(3.1) Total demand

(3.2) Total revenues

(3.3) Total investments

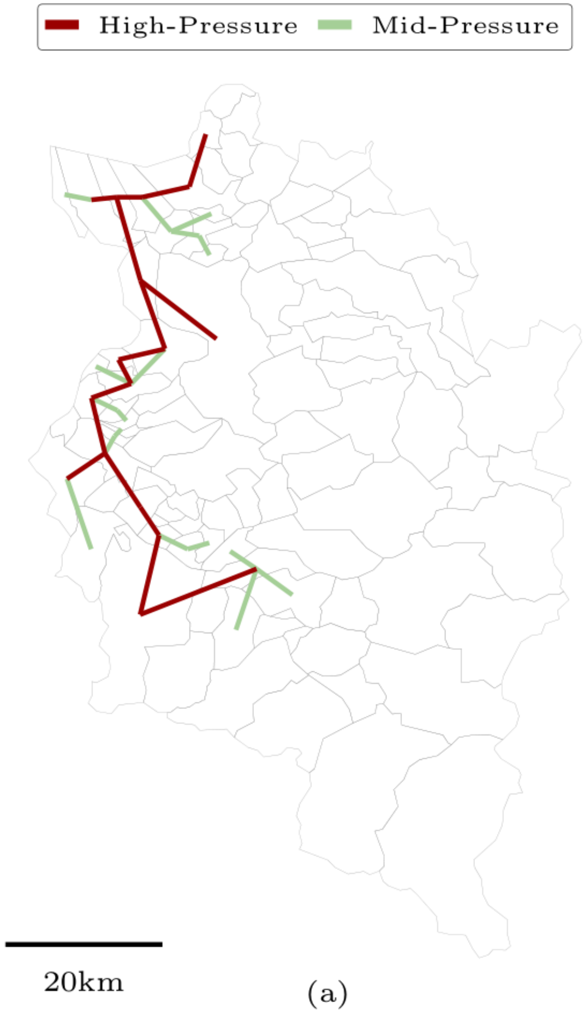
(3.4) Capex & Opex

			year	book value	capex	npv of capex	revenues	npv of revenues	npv of opex
	1.00	lamda (infinitesimal demand increase)	2 030	337	17	15	761	672	44.19
	0.87		2 031	330	16	14	761	656	43.11
	0.30		2 032	323	16	14	-	-	42.06
	0.09		2 033	316	16	13	-	-	41.04
	-		2 034	310	15	12	-	-	40.04
	-				5	12	-	-	39.06
	-				5	11	-	-	38.11
	-				4	11	-	-	37.18
	0.13		2 038	283	14	10	-	-	36.27
	0.30				14	10	-	-	35.39
	0.70				13	9	-	-	34.52
	0.96				13	9	-	-	33.68
	4.35	total gas demand increase	2 042	256	13	8	-	-	32.86
	x 175 EUR/MWh		2 043	249	12	8	-	-	32.06
	760.87	total revenues obtained by gas demand increase	2 044	242	12	8	-	-	31.28
			2 045	236	12	7	-	-	30.51
					11	7	-	-	29.77
					11	6	-	-	29.04
					11	6	-	-	28.33
length	investment costs		2 049	209	10	6	-	-	27.64
5.29	29 618	transmission	2 050	202	202	109	-	-	26.97
48.57	194 298	high-pressure				305		1 329	733
3.06	18 384	mid-pressure							
	336.53	total investment cost to supply lambda							- 290.1879

```
Solution:
- number of solutions: 0
  number of solutions displayed: 0
objective : Size=1, Index=None, Active=True
    Key  : Active : Value
    None :   True : 524810918.2384658
SHADOW PRICE : MID-PRESSURE GAS NETWORK DEMAND
2025 : -760.8695652173913
2026 : -742.3117709437964
2027 : -724.2066057988258
2028 : -706.543030047635
2029 : -689.310273217205
2030 : 0.0
2031 : -290.1878768621505
2032 : -640.0931136504277
2033 : -624.4810864882223
2034 : -609.2498404763145
2035 : -594.390088269575
```

(4) NPV

Cost-optimal network without ensured supply (CO)

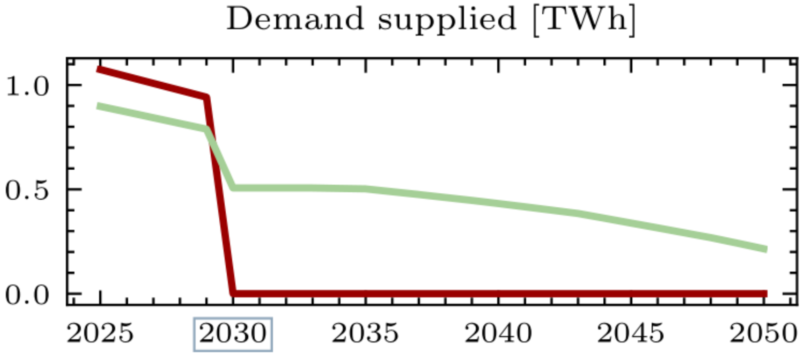


(a)

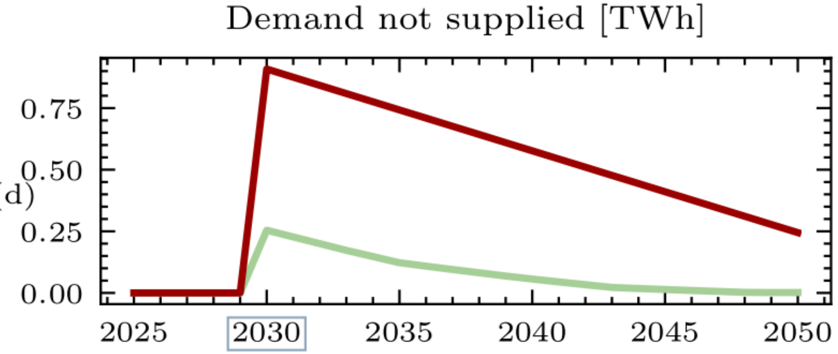
(b)

	High-Pres.	Mid-Pres.
Max. [MW]	161.92	40.58
Length [km]	84.5	57.2
Decom. [%]	0	41
Refurb. [%]	100	59

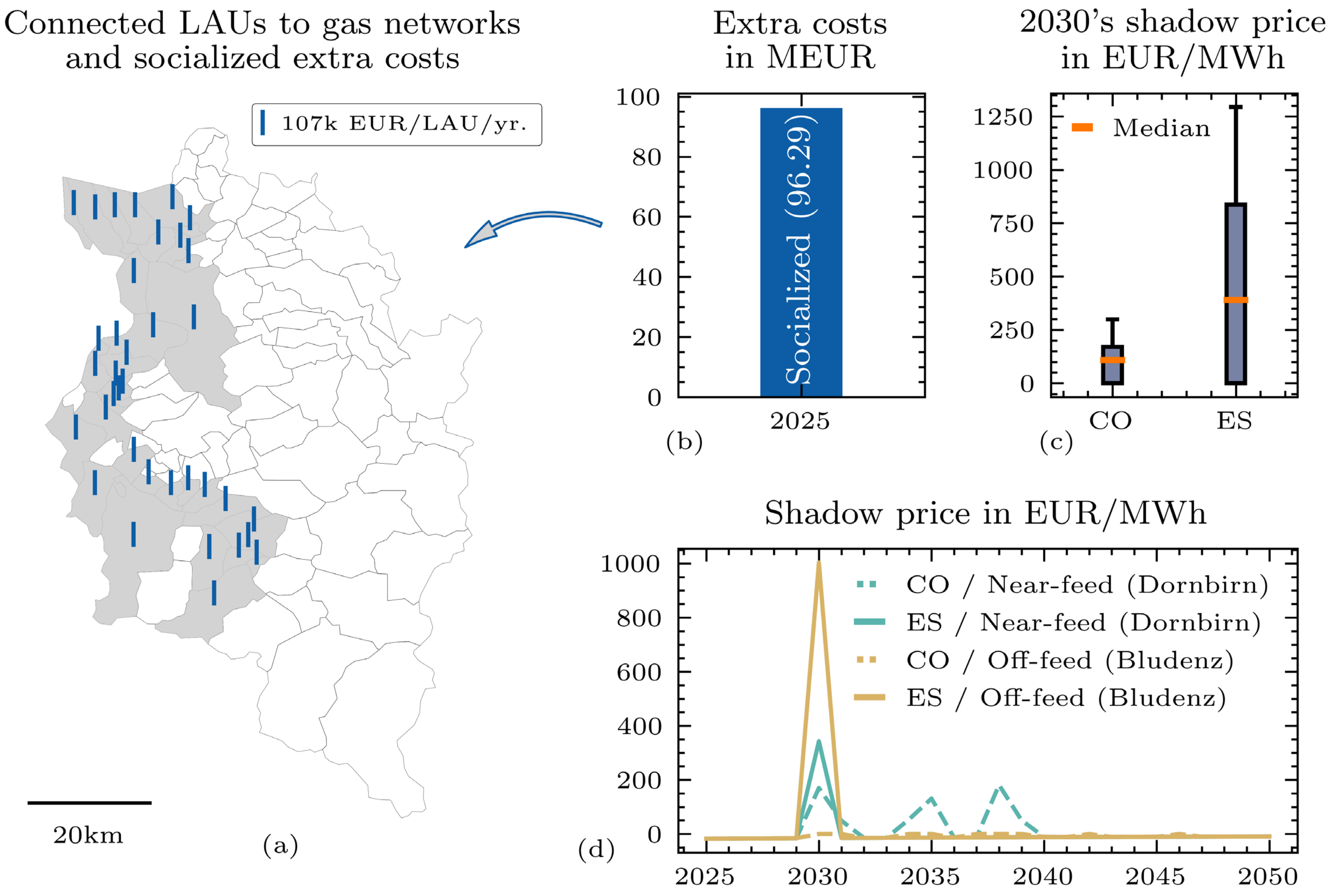
(c)



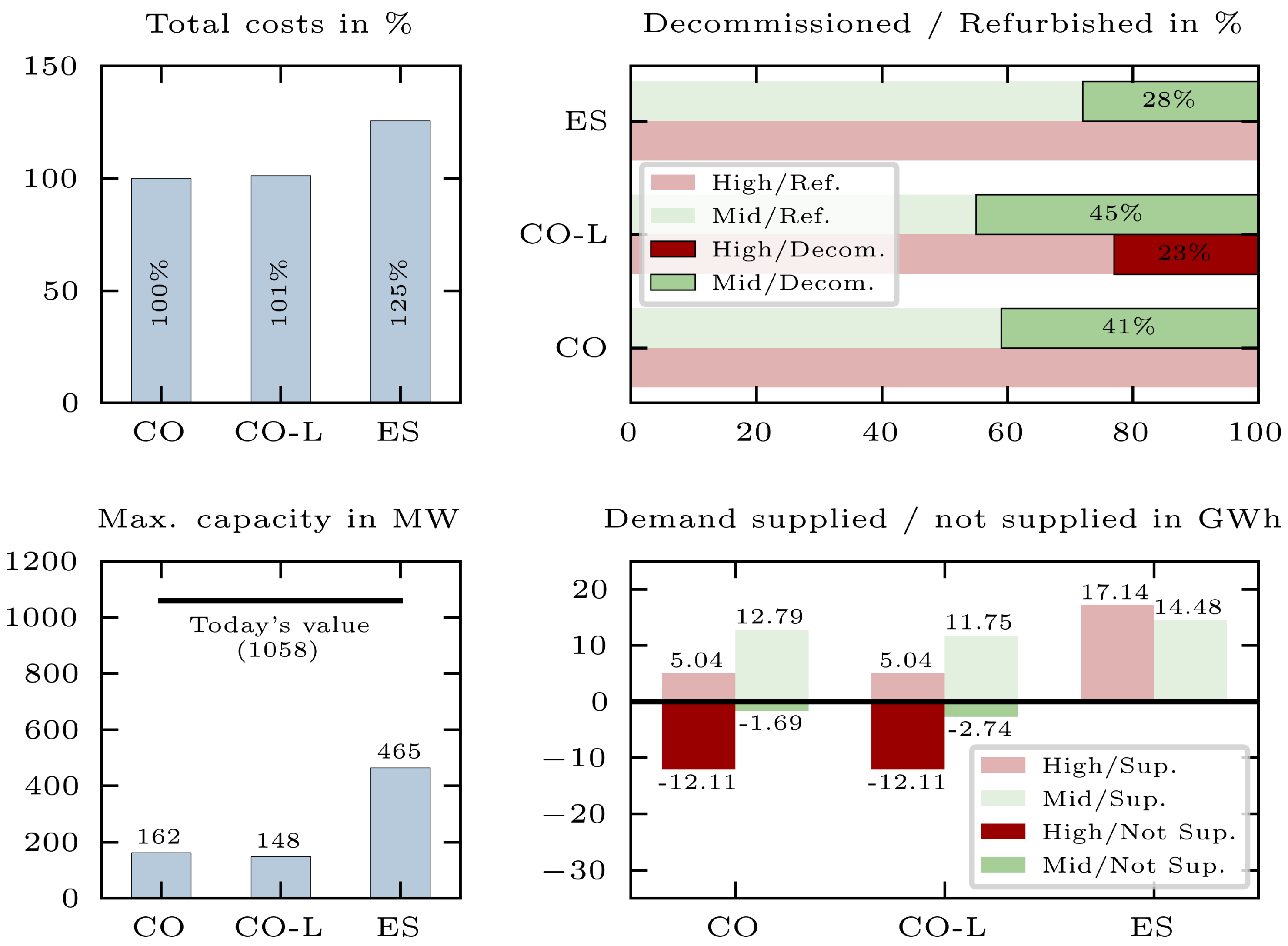
(d)



Comparison of network w/ ensured supply (CO & ES)



Overview: CO, ES and cost-optimal with lumpiness (CO-L)



Conclusions and recommendations

- In the future, **smaller gas networks** in both capacity and length will be necessary (regardless of secured supply) resulting from irreversible defossilization of energy services
- **Wide range of network design** between cost-optimal gas networks **w/ ensured supply** reveal crucial **trade-off** decisions for network operators in the future on how to deal with existing / available demands (i.e., decommissioning despite possible demands)
- **Shadow prices** of local gas balance constraints **indicate** that network operator should **strike a balance between cost-optimal gas network design w/ ensured supply** (e.g., flexibility and management of unexpected changes in (peak) gas demands)
- **Increased** network operator's **total costs** in case of ensured supply need to be **socialized** to a **few consumers** in the future (primarily at subordinate network / pressure levels)
- Influence of **socialized grid / network costs** on economic viability and **profitability** of **sustainable alternatives** substituting natural gas-based energy service needs and related trade-off decisions

Next EEG-Seminar (outlook)

Energy and Buildings
Volume 262, 1 May 2022, 112013

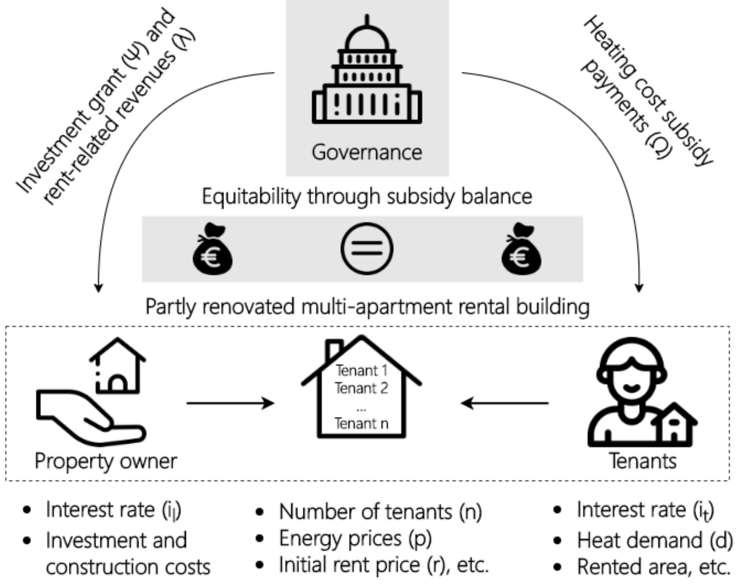
Equitable decarbonization of heat supply in residential multi-apartment rental buildings: Optimal subsidy allocation between the property owner and tenants

Sebastian Zwickl-Bernhard [a], Hans Auer [a], Antonia Golab [a]

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.enbuild.2022.112013 Get rights and content



Acknowledgements

Essential parts presented in this EEG-Seminar have been
developed within CF0437 in collaboration with Theresia, Antonia and Hans ☺
I would like to acknowledge this explicitly.

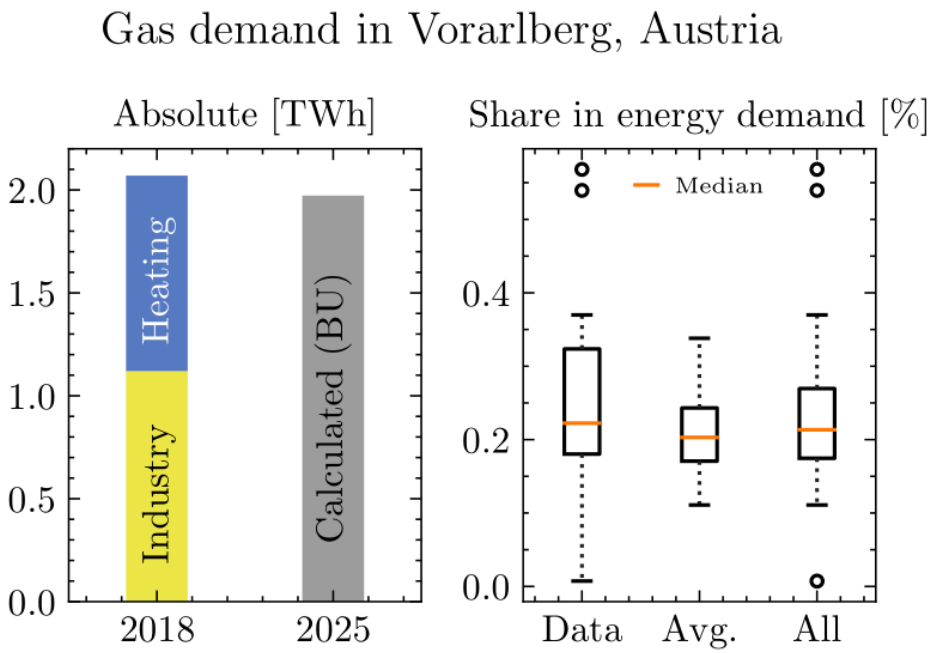
Sebastian Zwickl-Bernhard
PhD Candidate
Energy Economics Group (EEG)
Technische Universität Wien (TUW)
Karlsplatz 13, 1040 Wien, Austria
zwickl@eeg.tuwien.ac.at
https://github.com/sebastianzwickl
https://orcid.org/0000-0002-8599-6278

Nomenclature (variables & parameters)

Set and Index		
$p \in \mathcal{P} = \{1, \ldots, P\}$	Pipeline for gas transport, index by p	
$n \in \mathcal{N} = \{1, \ldots, N\}$	Node of the gas network, index by n	
$l \in \mathcal{L} = \{1, \ldots, L\}$	Gas network level (e.g., high-pressure), index by l	
$y \in \mathcal{Y} = \{1, \ldots, Y\}$	Years, index by y	
$m \in \mathcal{M} = \{1, \ldots, M\}$	Months, index by m	
Primal Decision Variables (Selection)		
$Capex$	Capital expenditures	EUR
$Opex$	Operational expenditures	EUR
Rev	Revenues generated by gas supply	EUR
$\gamma_{p,l,y}$	Capacity of pipeline p at l in y	MW, GW
$q^{dem}_{n,l,y,m}$	Gas demand supplied at n and l in y and m	MWh, GWh
$q_{p,l,y,m}$	Quantity of gas transported at p and l in y and m	MW, GW
$\Pi_{p,l,y}$	Book value of pipeline p at l in y	EUR

Dual Decision Variables		
$\lambda^{CO}_{n,l,y,m}$	Cost-optimal shadow price of gas supply without ensured supply at n and l in y and m	EUR/MWh
$\lambda^{ES}_{n,l,y,m}$	Cost-optimal shadow price of gas supply with ensured supply at n and l in y and m	EUR/MWh
Parameters (Selection)		
$\gamma^{pre}_{p,l,y}$	Pre-existing capacity of pipeline p at l in y	MW, GW
$d^{max}_{n,l,y,m}$	Maximum gas demand at n and l in y and m	MWh, GWh
$q^{fed}_{n,l,y,m}$	Quantity of gas fed in at n and l in y and m	MW, GW
c^{inv}_{l}	Specific refurbishment investment costs at l	EUR/MW/km
$\Pi^{pre}_{p,l,y}$	Book value of pre-existing pipeline p at n in y	EUR
$y^{inv}_{p,l}$	Year of refurbishment/decommissioning per p and l	1
ω	Weighted average cost of capital	%
i	Interest rate (for calculating the net present value)	%

Estimating local gas demands until 2050



Name	Residential	Industry	SMB	Service	Decline rate (2050's share)
Type A	✓				linearly until 2040
Type B	✓	✓	✓		linearly (15%)
Type C				✓	linearly (20%)
Type D		✓	✓		linearly (35%)

Table 3: Annual decline rates for different compositions of gas demands at the local community level under the naming convention and sectors of end-use from energiemosaik [58].