Design and Evaluation of Flexible Sector-Coupling Pathways in Future Urban Energy Supply Systems

10.09.2019 | TIMO KANNENGIESSER, PETER STENZEL, MARTIN ROBINIUS, DETLEF STOLTEN

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IEK-3: Institute of Electrochemical Process Engineering

Future Trends in District Energy Systems

Efficiency and climate protection targets

Additional energy demand from the integration of electric mobility

Urban heat shift requires defossilisation

Renewable energy integration via sector coupling

Scope

Starting point

Existing district (case study) in a densely populated urban area to be refurbished in 2020

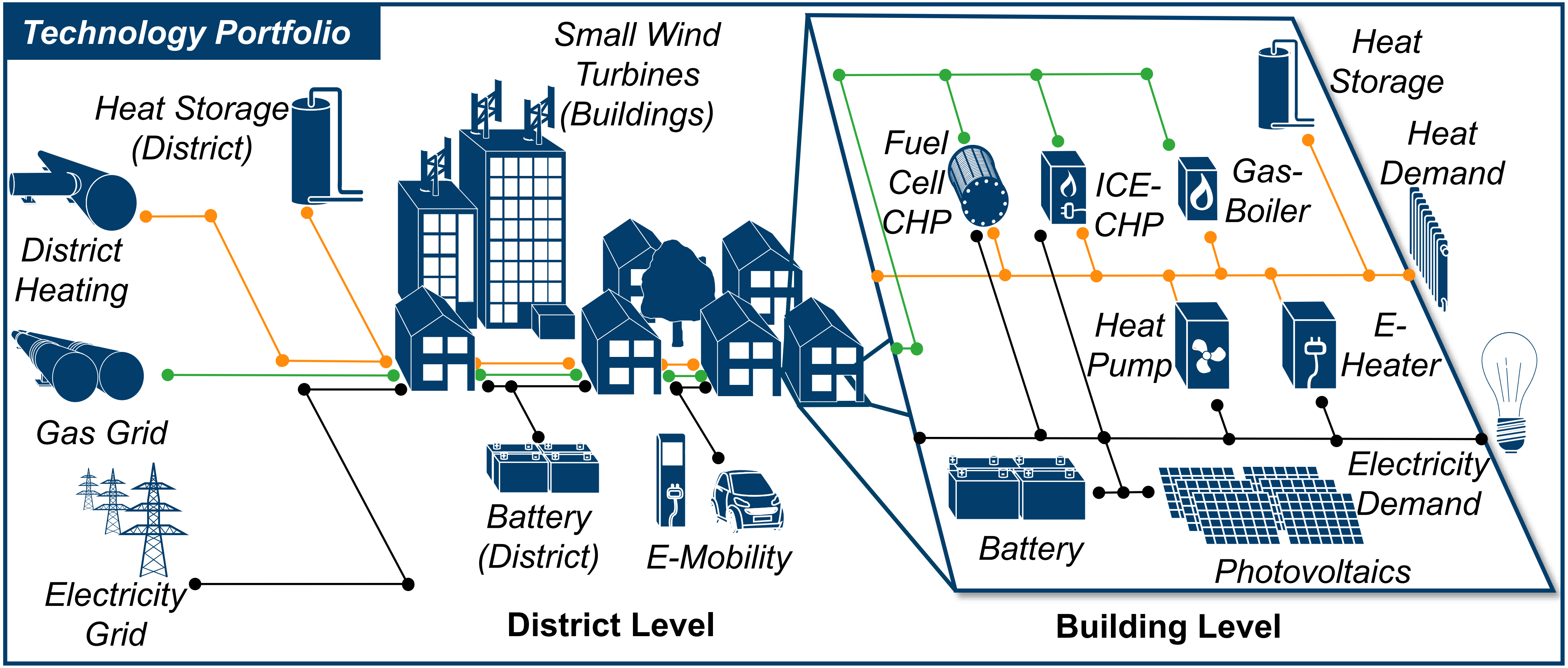
Key questions

- Which heat and electricity supply pathways are cost-optimal from today‘s point of view?
- Can the climate protection targets of 2030 and 2050 be achieved with these pathways?
- What is the role of building refurbishment measures?
- How will district energy consumption structures change under the influence of local generation and new consumers (electric mobility)?

Approach

- Comparative analysis and evaluation of sector coupling pathways with a district optimization model
- Selection of a district as a case study and consideration of current regulatory framework (EEG, KWKG)

District Optimization – Model Concept



Design and operation optimization for cost optimal district energy supply system under consideration of various **sector-coupling options** and an increasing **integration of electric mobility**

- Based on open source python package FINE [1]

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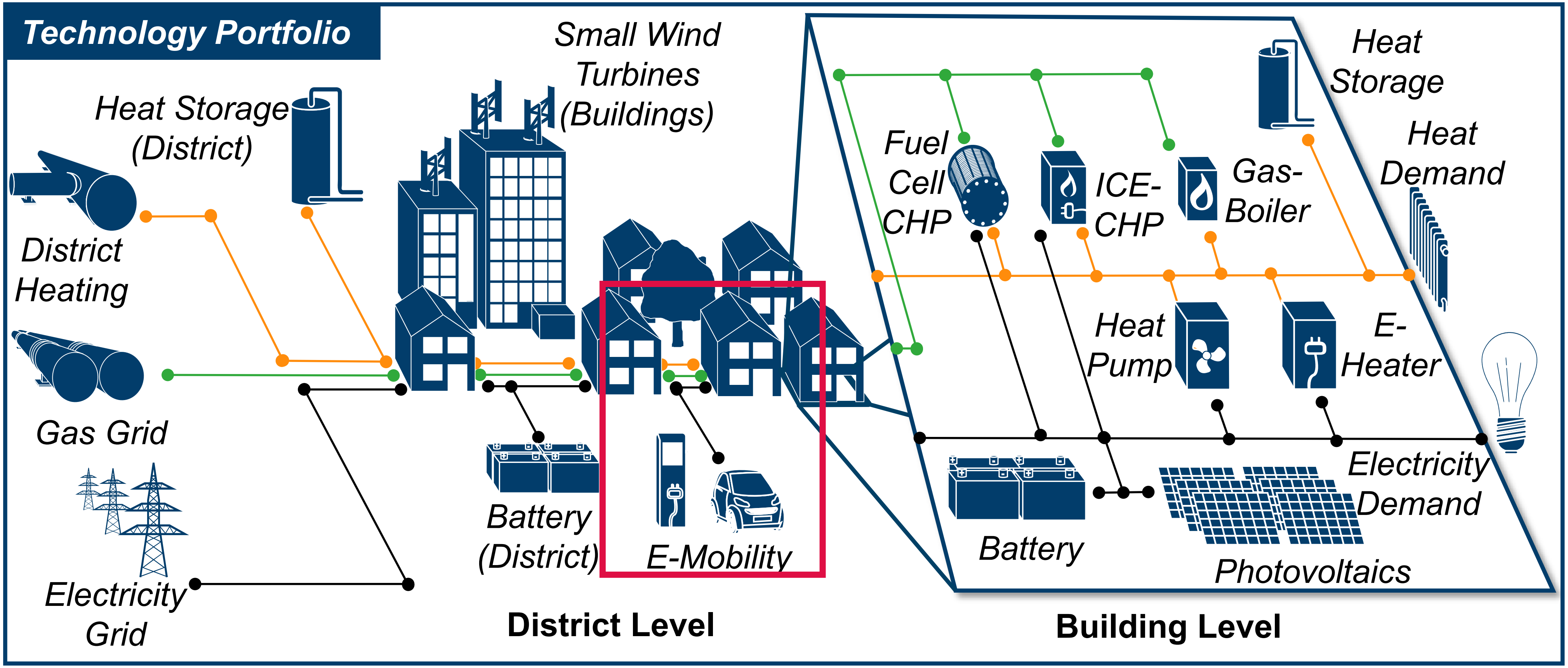

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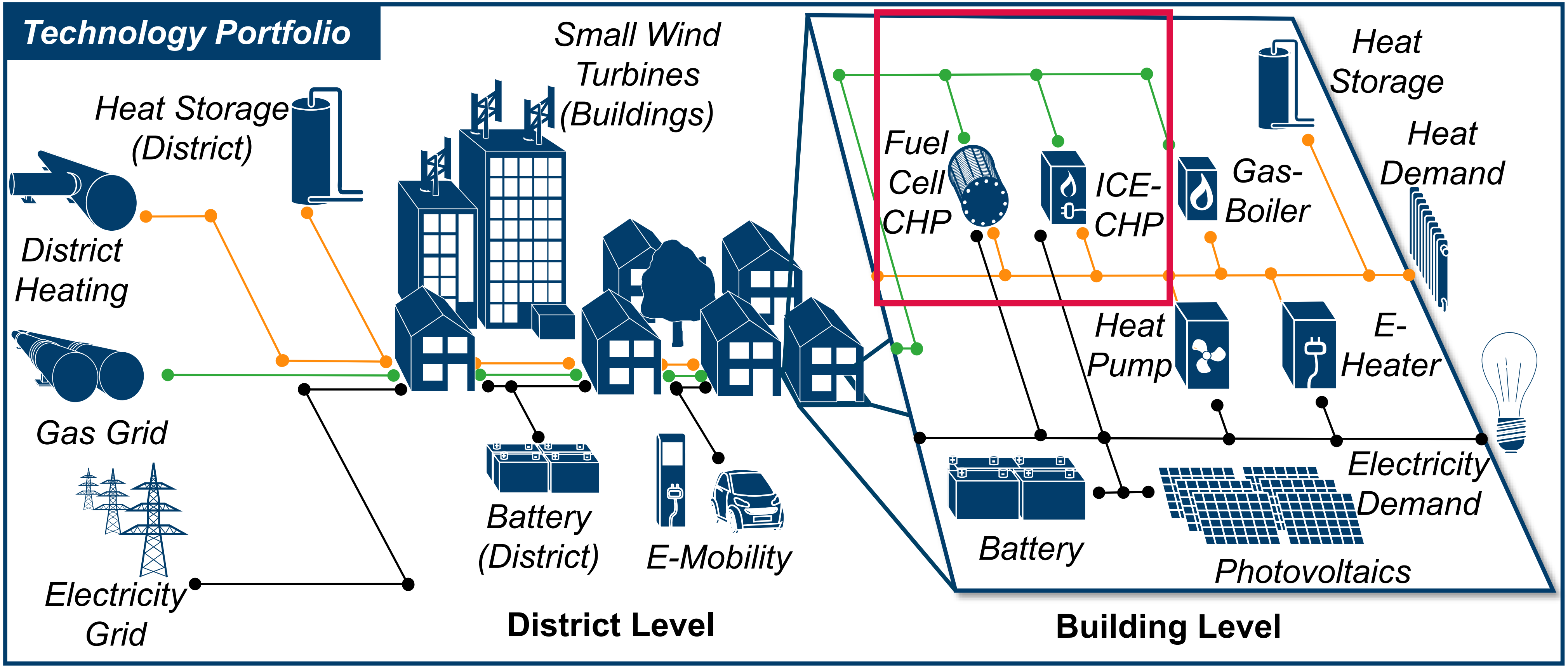

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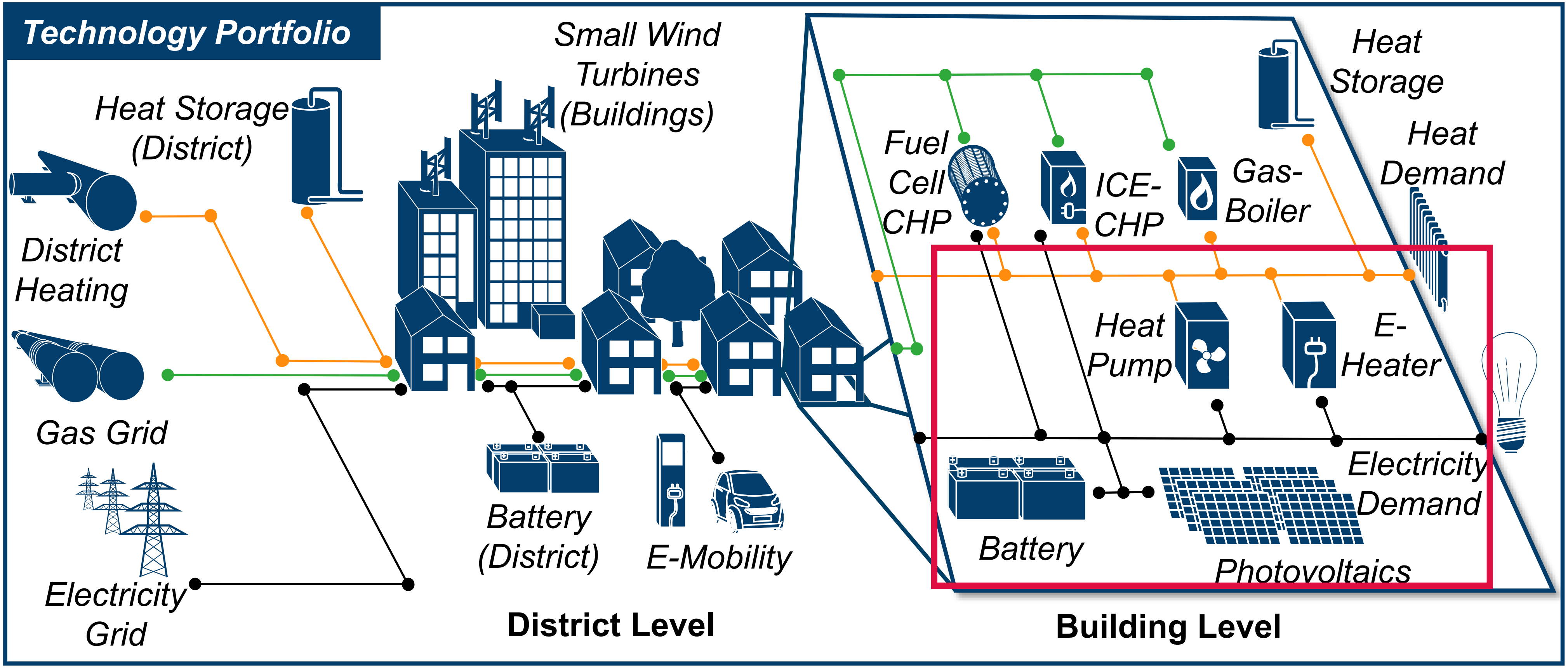

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District Optimization – Building Parameters (Case Study)

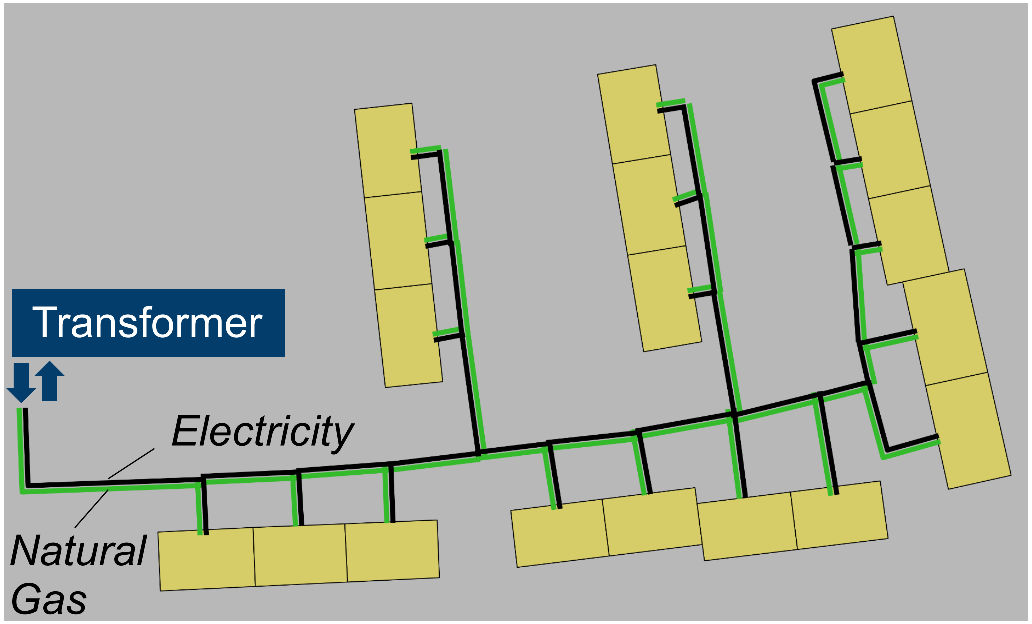
- Construction year: 1965
- 8 apartments per building
  - ~16 Inhabitants
- Adapted building shape based on TABULA database [1]
  - Type building: "*DE.N.MFH.05.Gen.ReEx.001.003*"
  - Living area: 640 m²
  - Roof area: 396 m²
  - Wall area: 515 m²
  - Windows area: 110 m²
  - Floor area: 396 m²
- Electricity demand from electric mobility
  - Share of 65% battery electric vehicles (BEV) per building (six BEV)

The pathway analysis includes two different building standards:

1. Existing buildings without refurbishment
   → Spec. Heating Load 152 kWh/m²
2. Existing buildings with comprehensive refurbishment (Wall, roof, windows, floor)
   → Spec. Heating Load 44 kWh/m² (Based on EnEV 2016)

[1] "TABULA - Scientific Report Germany - Further Development of the National Residential Building Typology" Institute for Housing and Environment (IWU), Darmstadt / Germany, 2012

District Optimization – Investigated District (Case Study)



- 18 Buildings with similar building parameters
- District peak load:
  - Electricity:
    - 349 kW_{el}
  - Heating:
    - 818 kW_{th}

District (18 Buildings)	
Domestic electricity demand [kWh_{el}/a]	389,184
Heating demand incl. hot water (without refurbishment) [kWh_{th}/a]	2,064,365
Heating demand incl. hot water (with refurbishment) [kWh_{th}/a]	816,798
BEV electricity demand [kWh_{el}/a]*	219,175
Max. installable PV capacities** [kWp]	622

*: Demand based in total on 95 BEVs
**: Optimizer determines the installed capacities

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Selected Pathways (Year 2020)

1. Reference (Without / With Refurbishment)
2. AllElectric (Without / With Refurbishment)
3. Boiler PV (Without / With Refurbishment)
4. CHP (Without / With Refurbishment)
5. SOFC HP (Without / With Refurbishment)

Demand

Electricity (domestic)

Heating

Electricity (BEV)

Grid Supply

- *Gas Network* 1 3 4 5
- *Electricity Grid* 1 2 3 4 5

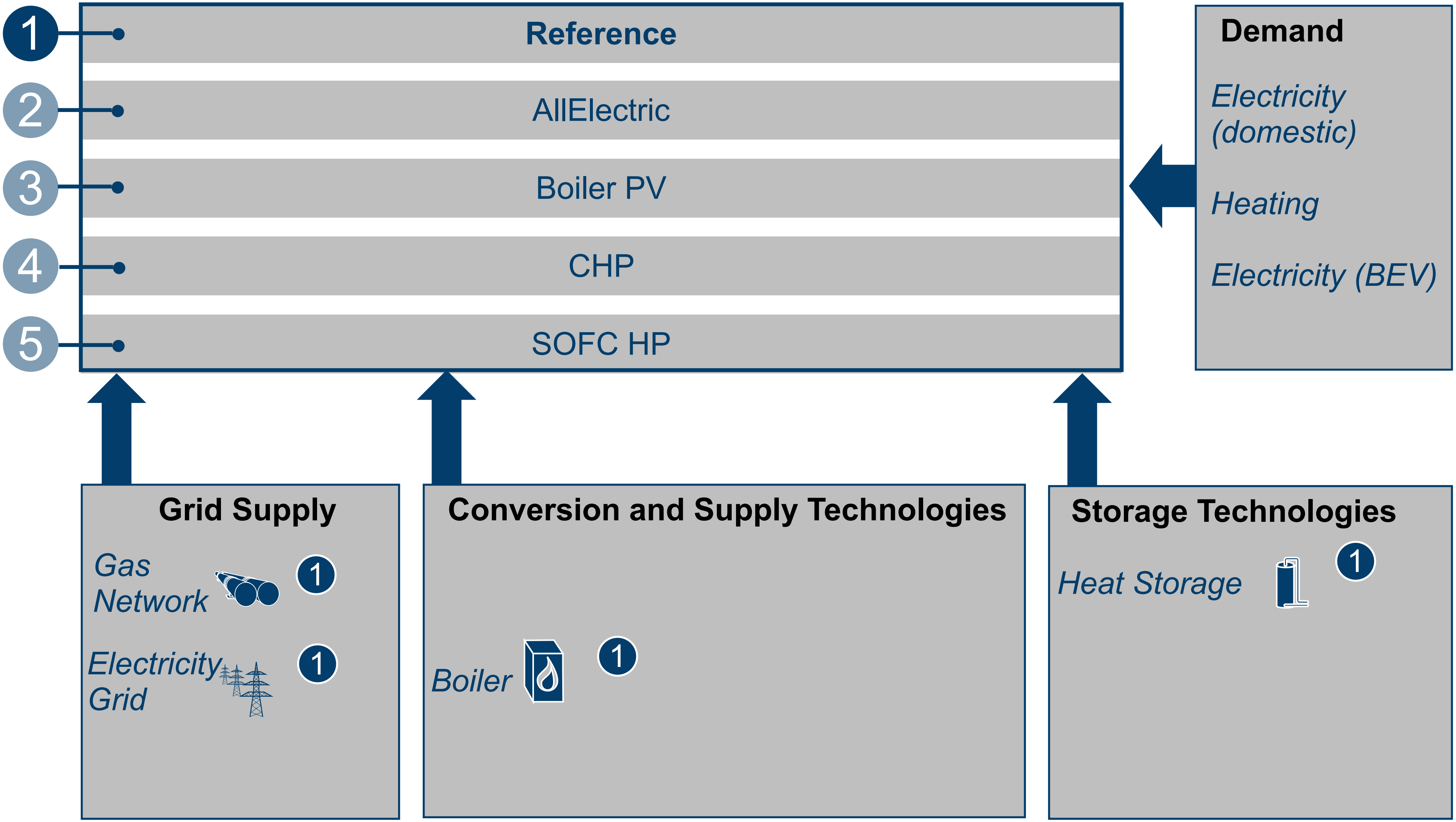
Conversion and Supply Technologies

- *PV* 2 3 4 5
- *SOFC* 5
- *Boiler* 1 3
- *Heat Pump* 2 5
- *CHP* 4

Storage Technologies

- *Heat Storage* 1 2 3 4 5
- *Battery* 2 3 4 5

Selected Pathways (Year 2020)



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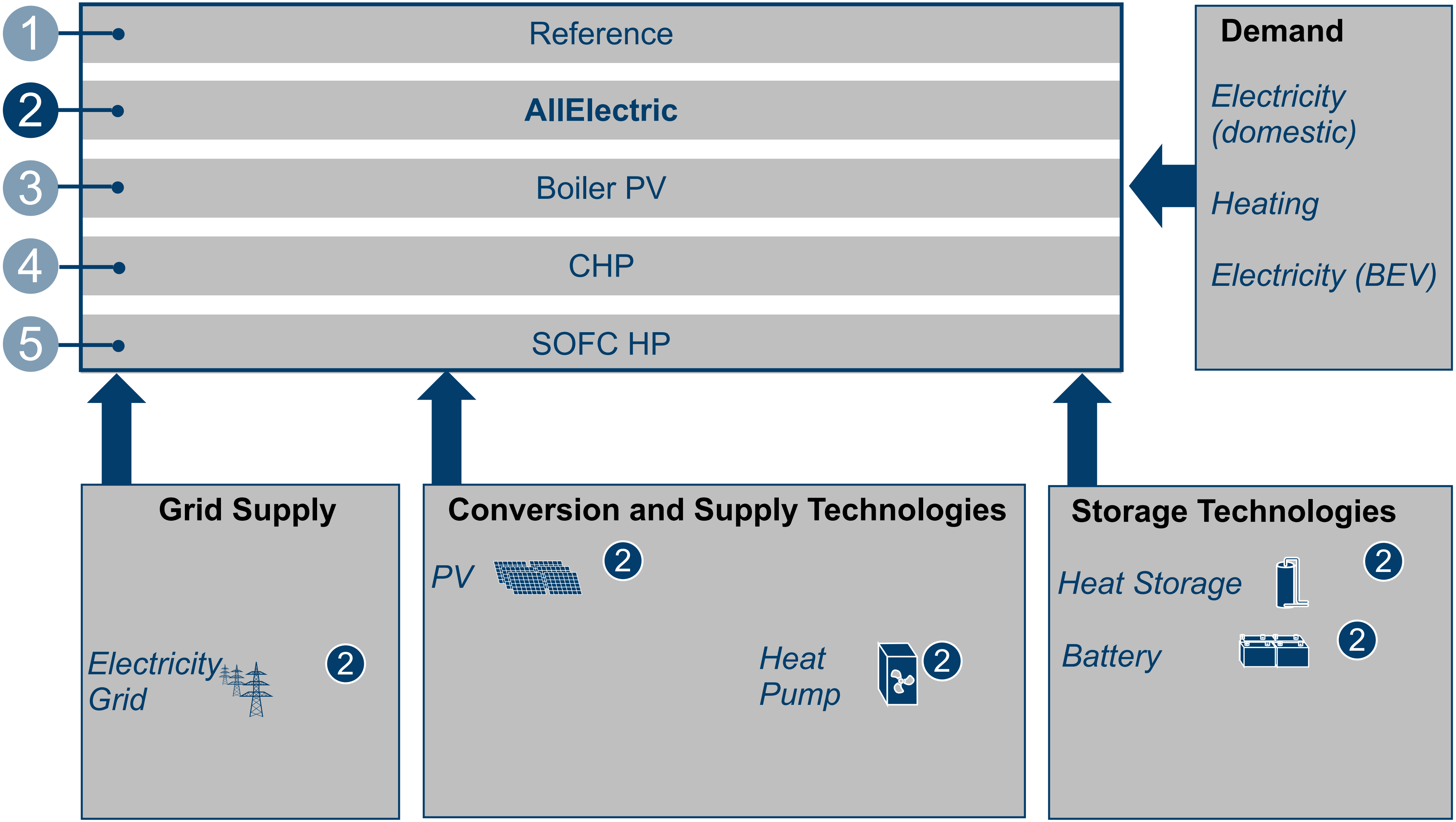

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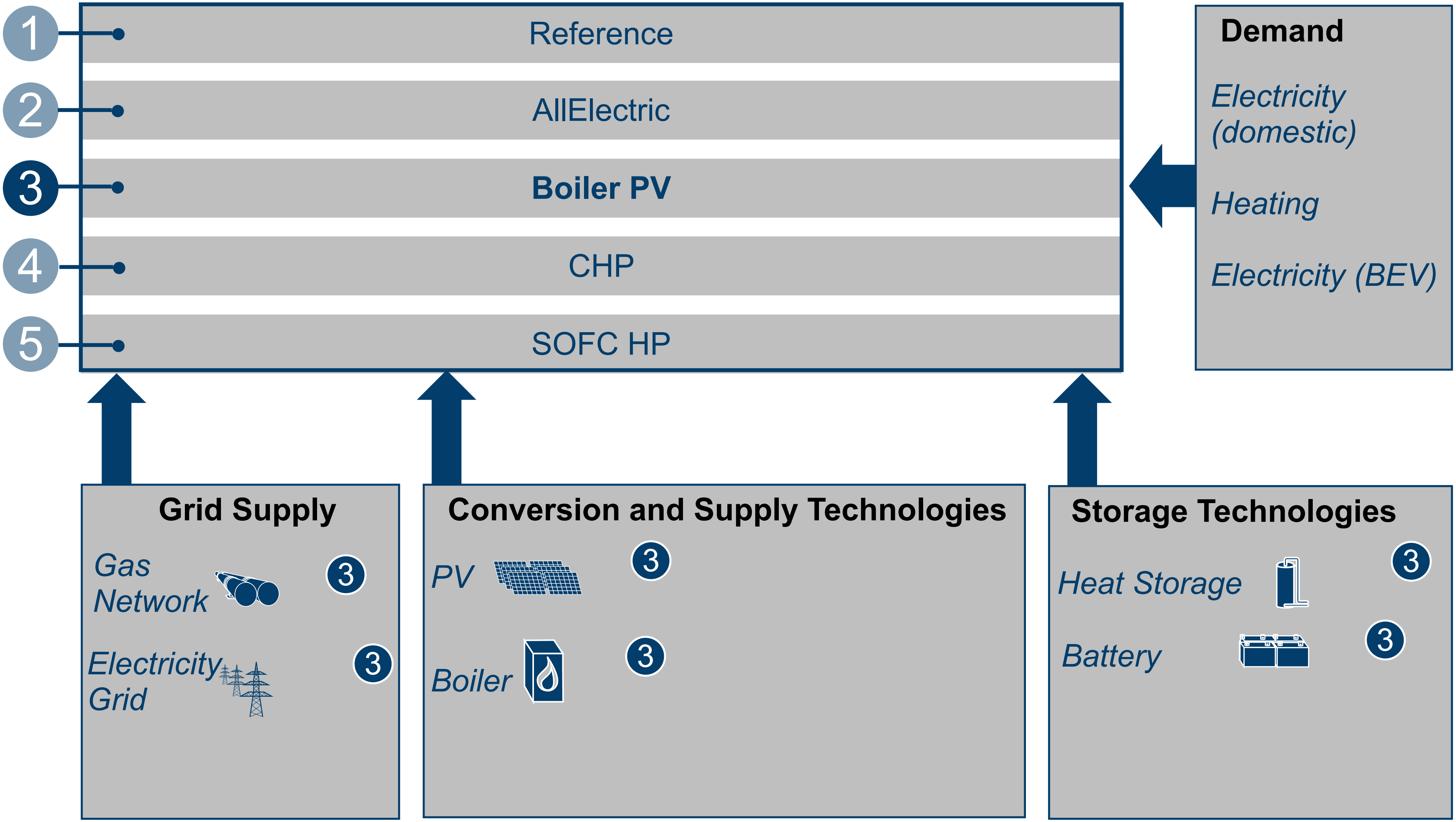
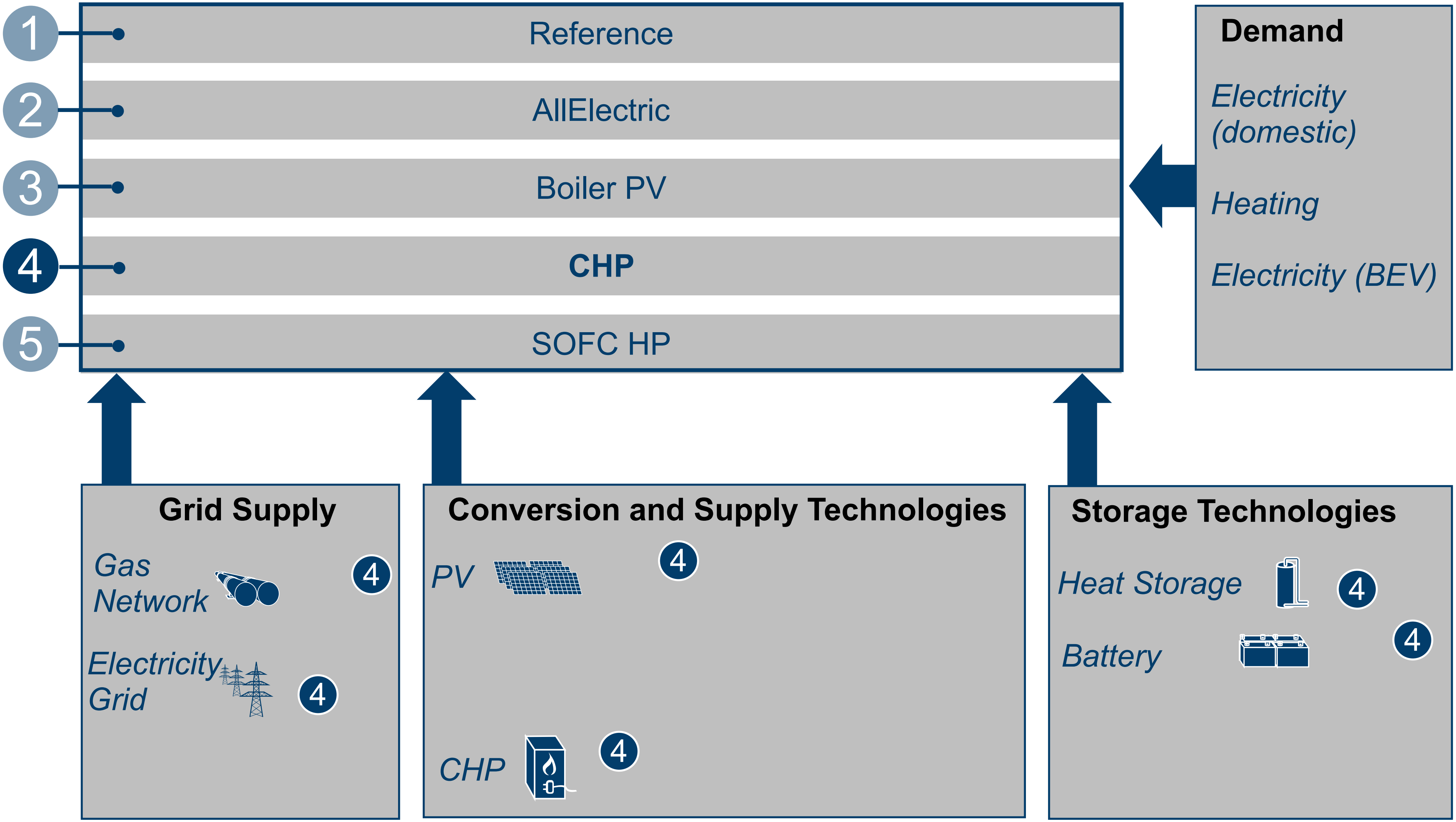


Selected Pathways (Year 2020)



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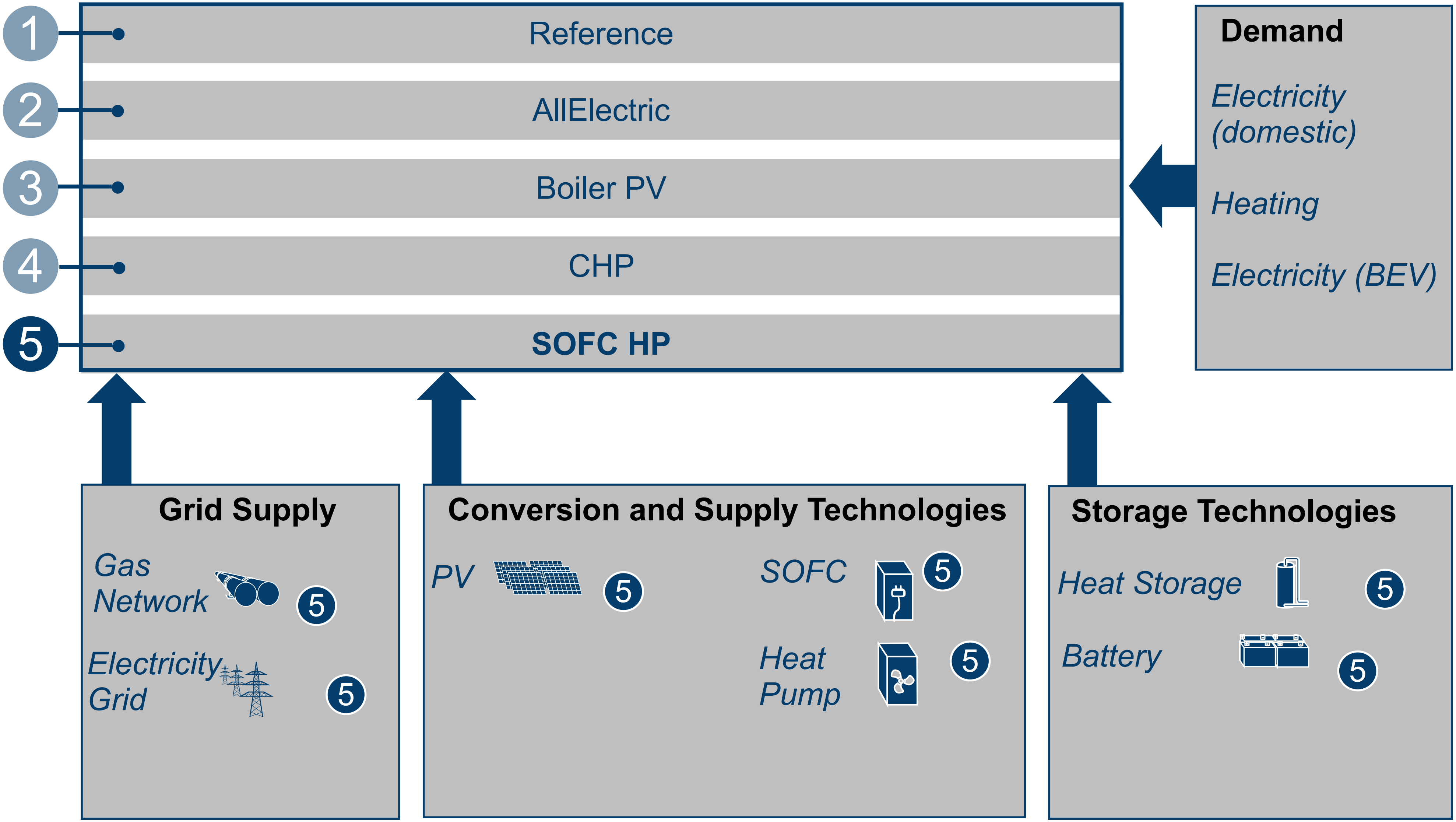
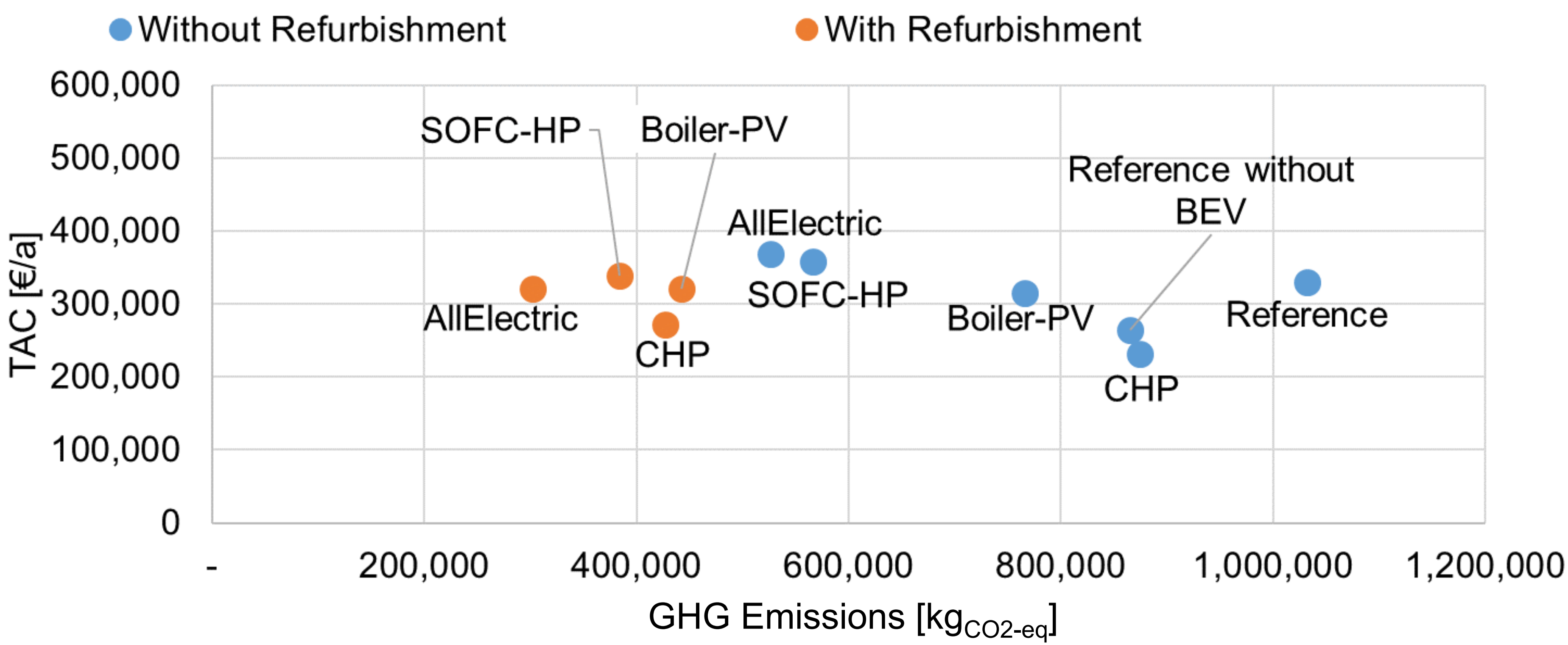
Selected Pathways (Year 2020)



Results – GHG*-Emissions 2020

Emission factors (kg_{CO2-eq}/kWh): based on [1,2]	Year	Electricity	Natural Gas
	1990	0.761	0.25
	2020	0.467	0.24

*GHG = Greenhouse Gases



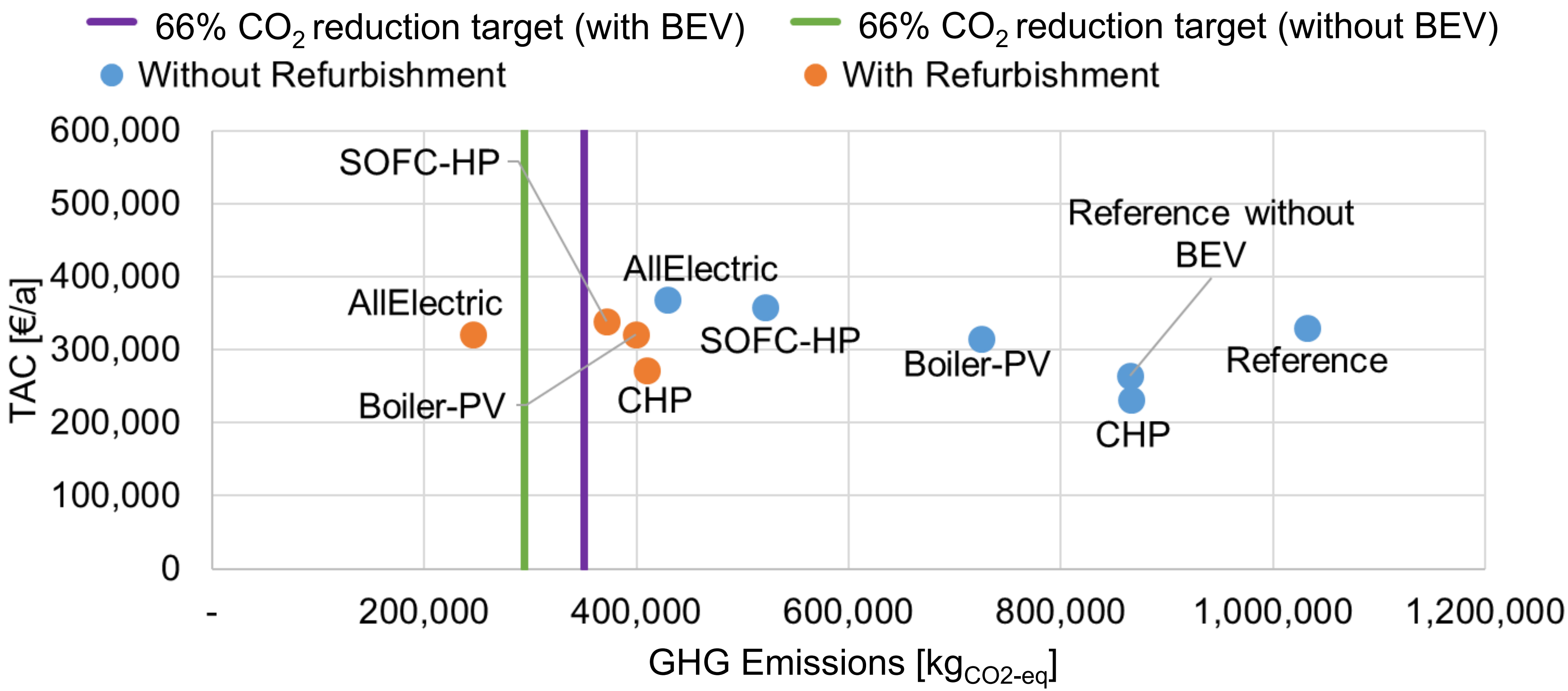
[1] Langfristszenarien für die Transformation des Energiesystems in Deutschland – Modul 2: Referenzszenario und Basisszenario, Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie, 2018

[2] DIN 18599, Energetische Bewertung von Gebäuden- Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung

Results – GHG*-Emissions 2030

Emission factors (kg_{CO2-eq}/kWh): based on [1,2]	Year	Electricity	Natural Gas
	1990	0.761	0.25
	2030	0.38	0.24

*GHG = Greenhouse Gases



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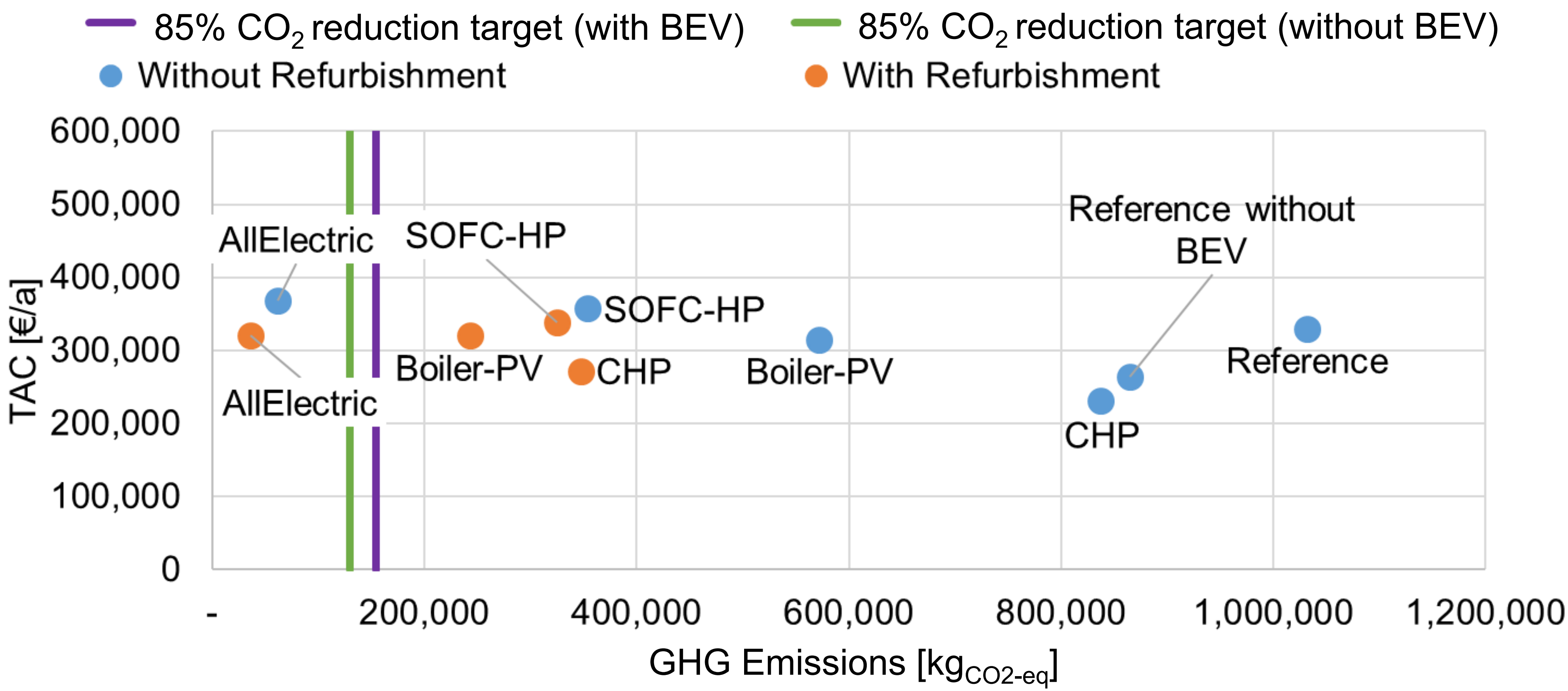
Results – GHG*-Emissions 2050

Emission factors (kg_{CO2-eq}/kWh): based on [1,2]	Year	Electricity	Natural Gas
	1990	0.761	0.25
	2050	0.055	0.24

*GHG = Greenhouse Gases



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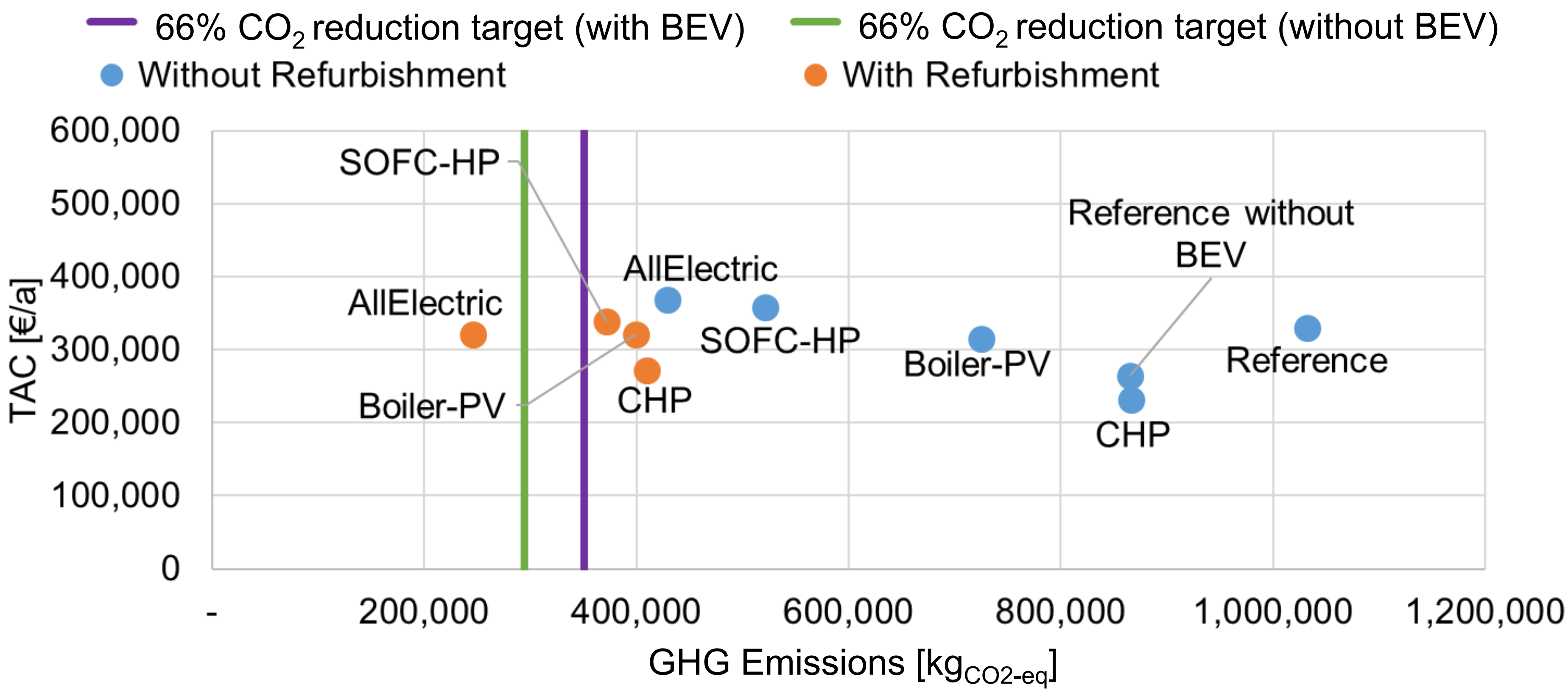
Parameter Variation – GHG*-Emissions 2030

Emission factors (kg_{CO2-eq}/kWh): based on [1,2]	Year	Electricity	Natural Gas
	1990	0.761	0.25
	2030	0.38	0.24

*GHG = Greenhouse Gases

Natural Gas Price: 6.07 ct/kWh



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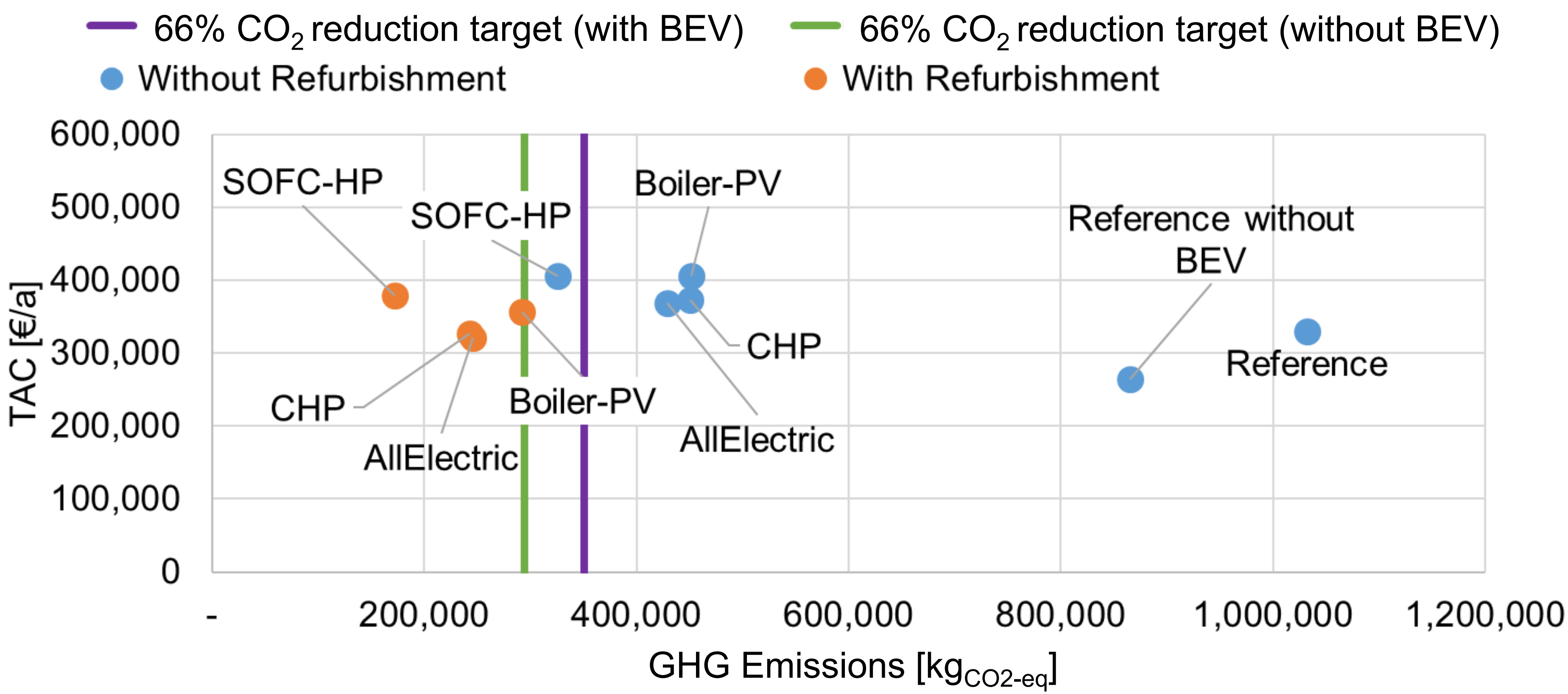
Parameter Variation – GHG*-Emissions 2030

Emission factors ($kg_{CO2\text{-}eq}$/kWh): based on [1,2]	Year	Electricity	Natural Gas
	1990	0.761	0.25
	2030	0.38	0.12

*GHG = Greenhouse Gases

100 % Biogas Price: 10.07 ct/kWh



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Wrap-up

Key findings from the selected case study (urban district with 18 multi family houses):

- Integration of electric mobility in building energy systems (sector coupling) increases local electricity demand in districts
- Currently CHP solutions show highest economic efficiency due to existing regulatory framework
- Cost of other pathways are in the same order of magnitude but differ significantly in terms of GHG emissions and energy demand
- Refurbishment is key to reduce GHG emissions and to reach efficiency targets
- All electric energy supply portfolios based on heat pumps can meet future GHG-Emission targets, however defossilisation of the electricity mix is a prerequisite
- CHP pathways require renewable gas to reach future GHG-Emission targets

➡ Integrated urban energy supply system optimization tools considering heat, electricity and energy demand from electric mobility on the one hand and a broad technology portfolio including sector coupling technologies on the other hand are key instruments for planners, utilities, grid operators…

Acknowledgement

This work has been supported by

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Die Initiative

Energie System 2050

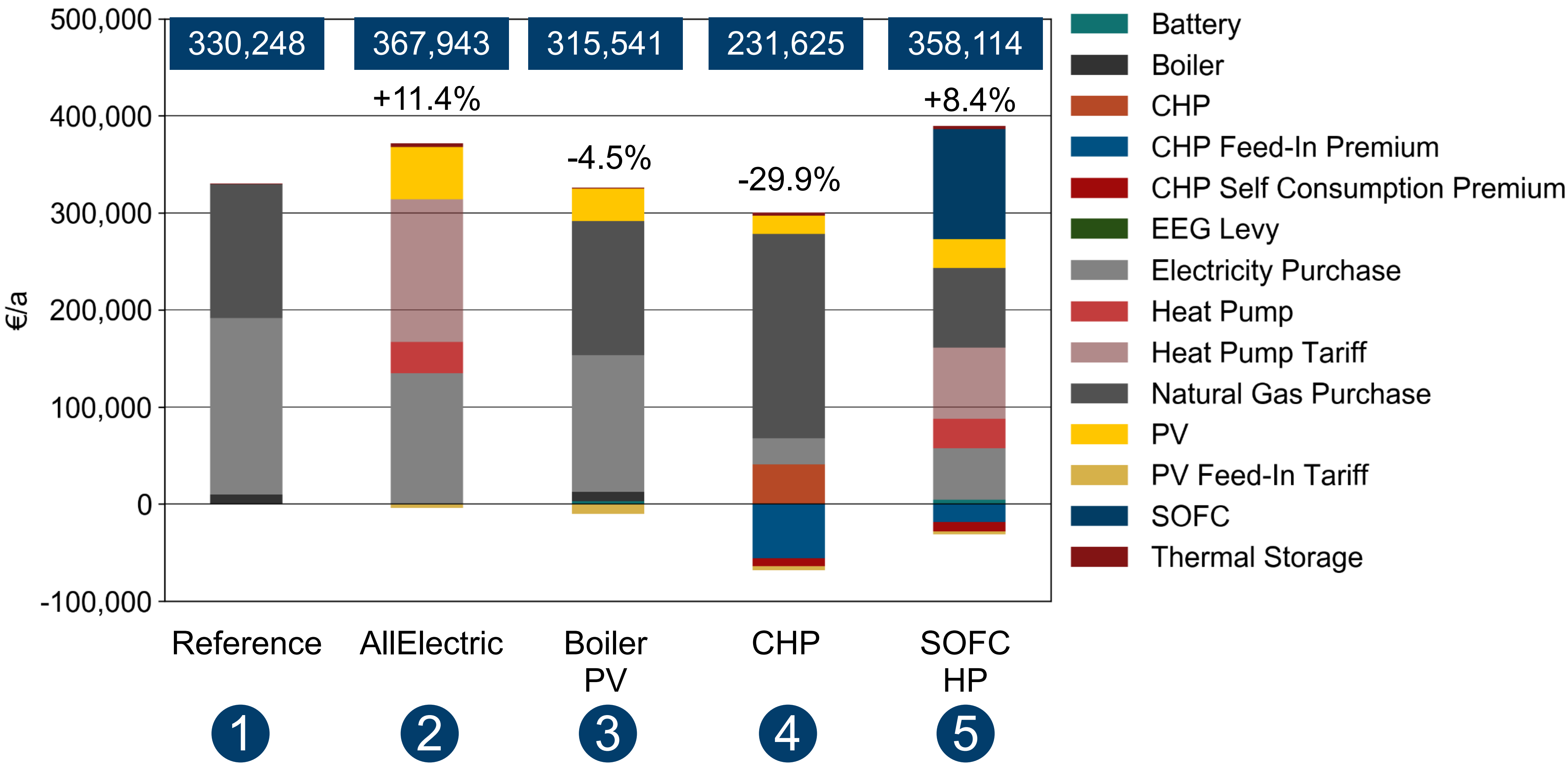
Ein Beitrag des Forschungsbereichs Energie

HELMHOLTZ GEMEINSCHAFT

Thank you for your attention

Appendix

District (Without Refurbishment) – Total Annual Costs (TAC)



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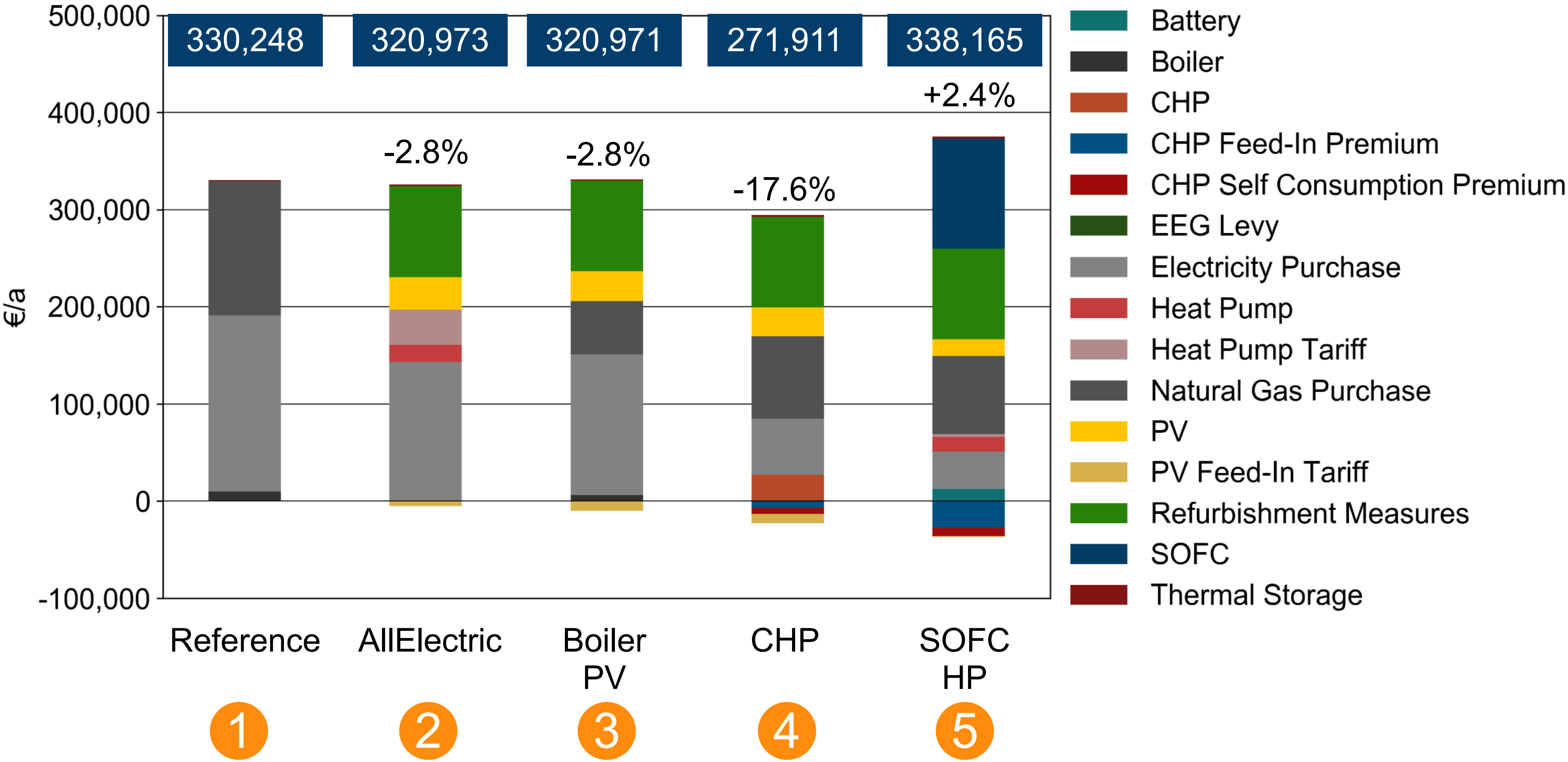
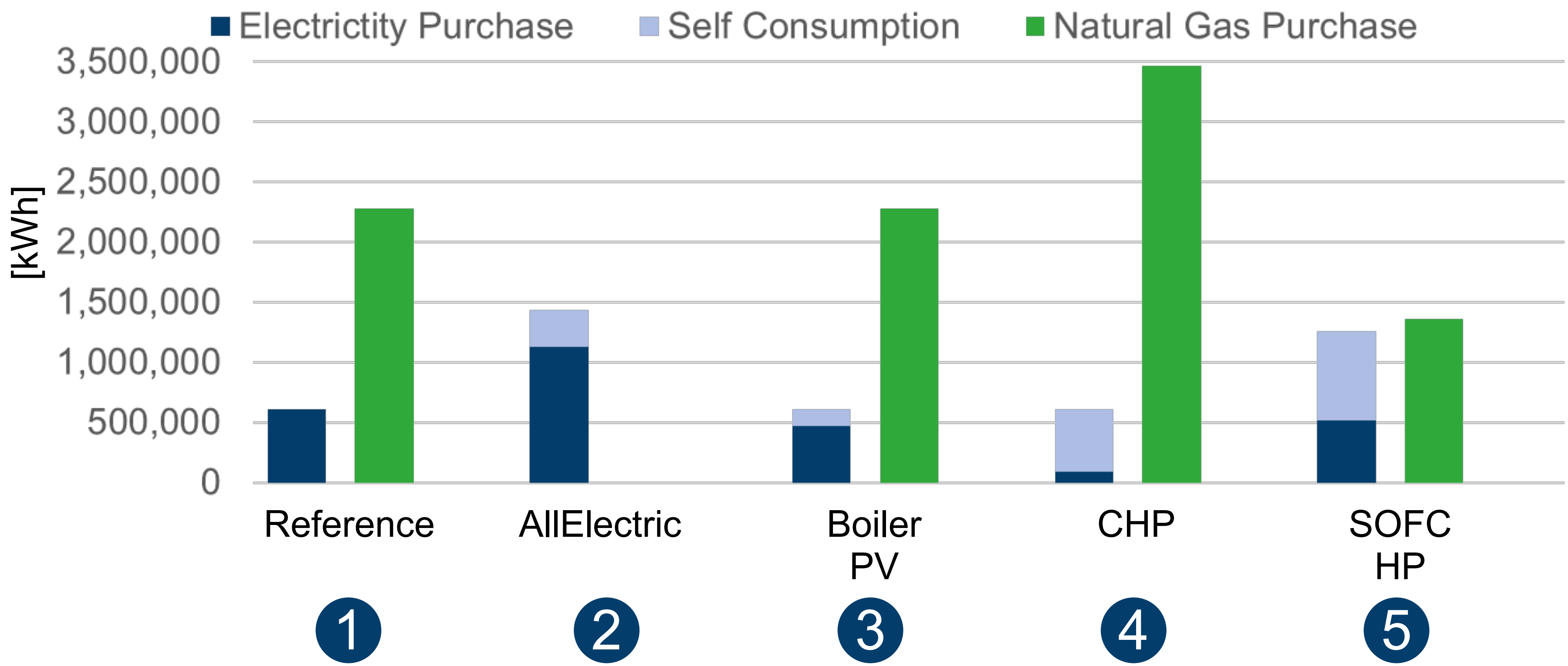
District (With Refurbishment) – Total Annual Costs (TAC)



District (Without Refurbishment) – Electricity and Natural Gas Purchase



	1	2	3	4	5
Self-Consumption % (Building| District)*	0 | 0	89.0 | 89.2	57.5 | 65.7	51.6 | 55.4	81.0 | 83.4
Autarky % (Building| District)*	0 | 0	21.6 | 21.7	22.7 | 25.9	84.9 | 91.3	59.1 | 60.9

*: Related to electricity

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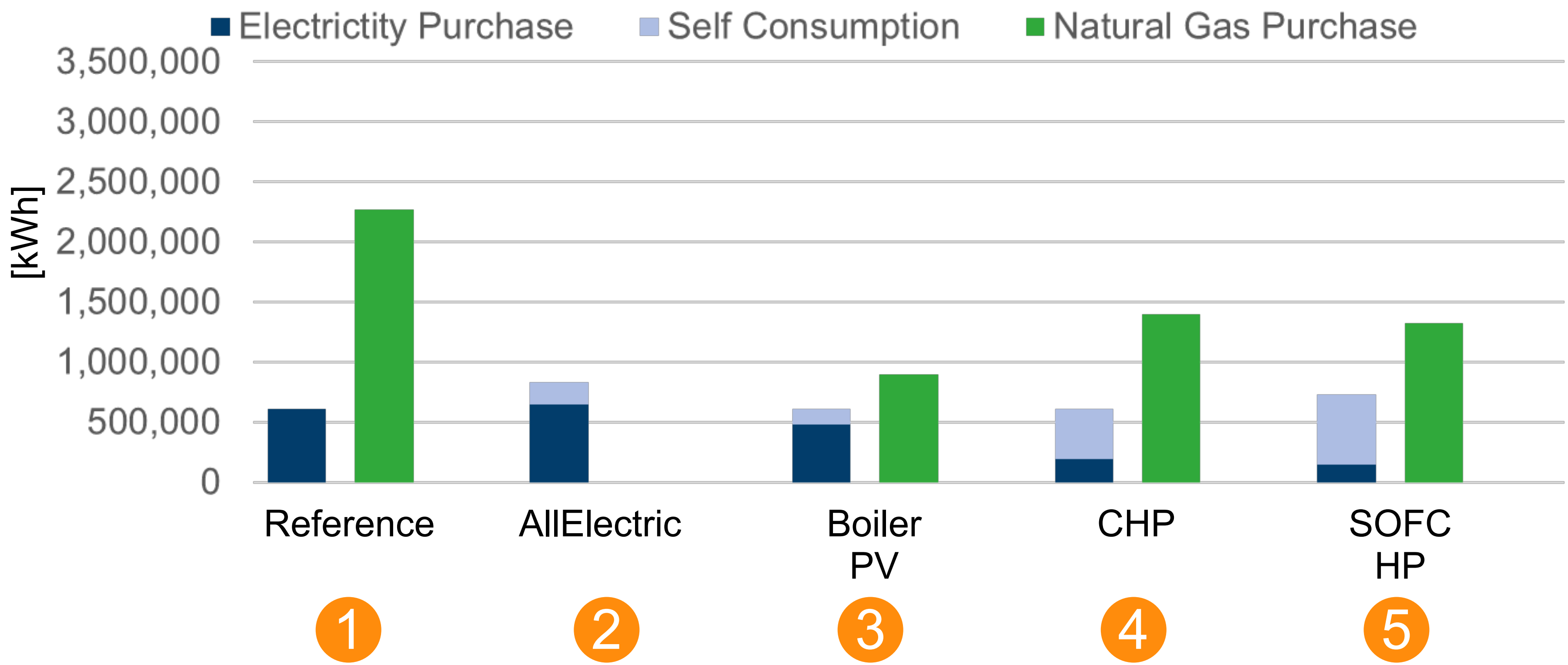
District (With Refurbishment) – Electricity and Natural Gas Purchase



Self-Consumption % (Building| District)*	0 | 0	78.9 | 82.8	55.3 | 65.5	73.7 | 77.5	72.0 | 75.2
Autarky % (Building| District)*	0 | 0	22.7 | 23.9	20.5 | 24.2	68.3 | 71.9	80.2 | 83.9

*: Related to electricity

District Optimization – Cost Assumptions (Germany, 2020)

Technologies	$CAPEX_{Cap}$	$CAPEX_{Fix}$	OPEX	Lifetime	Efficiency	Literature
PV	1,400 €/kW_p	1,000 €	1 % of CAPEX	25	-	[1-3]
Condensing Boiler	100 €/kW_{th}	2,800 €	1.5 % of CAPEX	20	90 %	[4-6]
Heat Pump	600 €/kW_{th}	5,000 €	1 % of CAPEX	20	COP = 2.5	[2,4,5]
ICE-CHP	1000 €/kW_{el}	15,000 €	7 % of CAPEX	20	25 $\%_{el}$ 60 $\%_{th}$	[5,7]
SOFC-CHP*	6,345 €/kW_{el}	4,441 €	7 % of CAPEX	8	52 $\%_{el}$ 33 $\%_{th}$	[8,9]
Thermal Storage	34 €/kWh_{th}	23 €	0 %	25	99.9 %**	[5,10]
Battery	700 €/kWh_{el}	2,000 €	0 %	15	90.0 %***	[11-13]

* KFW subsidy included
**Self discharge of 0.5%
***Self discharge of 0.01%

District Optimization – Cost Assumptions (Germany, 2020)

				Comments
Interest rate		4 %		Own assumption
Household Electricity Price		0.2988 €/kWh	[14]	
Heat Pump Electricity Price		0.2171 €/kWh	[14]	
Household Natural Gas Price		0.0607 €/kWh	[14]	
Household Biogas Price		0.1007 €/kwh	[15]	
PV Feed-In Tariff	<= 10 kWp	0.1003 €/kWh	[16]	continuous decrease of 1% compared to today
	<= 40 kWp	0.0979 €/kWh	[16]	
CHP Premium	<= 50 kW_{el}	0.08 €/kWh	[17]	60,000 full load hour
CHP-Index		0.0372 €/kWh	[18]	mean of last 3 years
CHP Self Consumption		0.04 €/kWh	[17]	60,000 full load hour
Avoided network tariffs		0,00995 €/kWh	[19]	
EEG Levy		0.0669 €/kWh	[20]	mean of last 3 years

Electricity (GHG Factor)	0.467 kg_{CO2eq}/kWh [21]
Natural Gas (GHG Factor)	0.24 kg_{CO2eq}/kWh [22]

Literature

[1] Markus Löhr. Systempreise Pv 2015 - Kurzauswertung der Angebotsdatenbank des Photovoltaikforum.com. Report, Denkzentrale Energie GmbH, 2016.

[2] Karen Byskov Lindberg, Gerard Doorman, David Fischer, Magnus Korp°as, AstridA° nestad, and Igor Sartori. Methodology for optimal energy system design of Zero Energy Buildings using mixed-integer linear programming. Energy and Buildings,127:194–205, 2016a. ISSN 03787788. doi: 10.1016/j.enbuild.2016.05.039.

[3] Frauenhofer ISE. Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale Pv Systems. Report, Study on behalf of Agora Energiewende, 2015.

[4] Philip Sterchele, Doreen Kalz, and Andreas Palzer. Technisch-ökonomischeAnalyse von Maßnahmen und Potentialen zur energetischen Sanierung im Wohngebäudesektor heute und für das Jahr 2050. Bauphysik, 38(4):193–211, 2016. ISSN 01715445. doi: 10.1002/bapi.201610022.

[5] Rita Streblow and Katrin Ansorge. Genetischer Algorithmus zur kombinatorischen Optimierung von Gebäudehülle und Anlagentechnik. Report, 2017.

[6] D. Lauinger, P. Caliandro, J. Van herle, and D. Kuhn. A linear programming approach to the optimization of residential energy systems. Journal of Energy Storage, 7:24–37, 2016. ISSN 2352152X. doi: 10.1016/j.est.2016.04.009.

[7] ASUE. BHkw-Kenndaten 2014/2015 - Module, Anbieter, Kosten. Report, Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch e.V., 2015.

[8] Solid Power GmbH, last access: 17.05.2019 ,https://www.solidpower.com/

[9] KFW, Energieeffizient Bauen und Sanieren – Zuschuss Brennstoffzelle (433)

[10] Jakob M. F. Rager. Urban Energy System Design from the Heat Perspective using mathematical Programming including thermal Storage. Thesis, 2015. URL http: //infoscience.epfl.ch/record/210788/files/EPFL_TH6731.pdf.

[11] Anna-Lena Klingler. Self-consumption with Pv + Battery systems: A market diffusion model considering individual consumer behaviour and preferences. Applied Energy, 205:1560–1570, 2017. ISSN 03062619. doi: 10.1016/j.apenergy.2017. 08.159.

Literature

[12] Jochen Linssen, Peter Stenzel, and Johannes Fleer. Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles. Applied Energy, 2015. ISSN 03062619. doi: 10.1016/j.apenergy.2015.11.088.

[13] „Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher 2.0 - Jahresbericht 2017“Institut für Stromrichtertechnik und Elektrische Antriebe der RWTH Aachen (ISEA), 2017

[14] „Monitoringbericht 2018" Bundesnetzagentur Deutschland, 2018.

[15] Naturstrom GmbH, naturstrom biogas, Last access: 17.05.2019 , https://www.naturstrom.de/privatkunden/gas/

[16] Bundesnetzagentur Deutschland, "EEG-Registerdaten und EEG-Fördersätze", 2017

[17] Bundesministerium der Justiz und für Verbraucherschutz, „https://www.gesetze-im-internet.de/kwkg_2016/ “

[18] European Energy Exchange Ag: Üblicher Strompreis gemäß KWK-Gesetz. 2018. Verfügbar unter: https://www.eex.com/de/marktdaten/strom/spotmarkt/kwk-index/kwk-index-download

[19] Westnetz GmbH, last access: 17.05.2019, https://iam.westnetz.de/ueber-westnetz/unser-netz/netzentgelte-strom

[20] Energielexikon, Bundesnetzagentur, last access: 17.05.2019 https://www.bundesnetzagentur.de/SharedDocs/FAQs/DE/Sachgebiete/Energie/Verbraucher/Energielexikon/EEGUmlage.html

[21] DIN 18599, Energetische Bewertung von Gebäuden- Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung

[22] Langfristszenarien für die Transformation des Energiesystems in Deutschland – Modul 2: Referenzszenario und Basisszenario, Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie, 2018

District (Without Refurbishment) - Installed Capacities

	Reference	AllElectric	Boiler PV	CHP	SOFC HP
Battery [kWh_{el}]	0	0	20	0	30
Boiler [kW_{th}]	585	0	585	0	0
CHP [kW_{th}]	0	0	0	503	0
Heat Pump [kW_{th}]	0	490	0	0	453
PV [kWp]	0	475	290	159	256
SOFC [kW_{th}]	0	0	0	0	51
Thermal Storage [kWh_{th}]	340	1826	340	1332	1293

District (With Refurbishment) - Installed Capacities

	Reference	AllElectric	Boiler PV	CHP	SOFC HP
Battery [kWh_{el}]	0	0	0	0	146
Boiler [kW_{th}]	585	0	228	0	0
CHP [kW_{th}]	0	0	0	249	0
Heat Pump [kW_{th}]	0	200	0	0	150
PV [kWp]	0	292	269	254	143
SOFC [kW_{th}]	0	0	0	0	51
Thermal Storage [kWh_{th}]	340	957	511	1078	922

Top-Down and Bottom-Up Load