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Scenarios for the decarbonization of district heating: the case of Leipzig

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***Abstract*— This study derives the levelized cost of heat (LCOH) for exemplary post-fossil district heating (DH) scenarios. The DH system of Leipzig in 2040 under the assumption of a completely climate-neutral heat supply is considered. Accordingly, four generation scenarios (GS) are proposed based on different energy carriers that are characterized as follows: (1) natural gas with carbon capture and storage, (2) hydrogen, (3) diversified mix of biomass, waste heat and solar, and (4) electricity. In addition, the scenarios' robustness toward commodity prices is investigated using a sensitivity analysis. A modeling environment was used to optimize the hourly economic dispatch. Based on this, levelized costs are determined. For the reference case, the LCOH of the GS 1 and 2 exceeds the LCOH of GS 3 and 4. Furthermore, the results indicate that relying on singular energy carriers as opposed to diversified generation portfolios leads to less robust LCOH regarding price sensitivities.**

***Index Terms*-- Decarbonization, District heating, Levelized cost of heat, Mixed integer linear programming**

I. Introduction

A. Motivation

The German Climate Change Act sets ambitious targets for emissions reductions in all sectors of the economy, including the building sector. However, recent years have shown that the building sector has not been able to meet the caps set for emissions [1, 2]. In order to achieve the target emission reduction of 68% by 2030 compared to 1990, the building sector must find new ways to reduce emissions [3]. One way to contribute to decarbonization is to reduce emissions in district heating systems, which provide a modest 8% of Germany's heat demand, with the potential to expand [4]. Only 14% of heat demand is currently met by renewables [5]. Therefore, reducing emissions in the heat supply contributes to the decarbonization of the entire building sector. Moreover, the centralized heat generation portfolio can provide an economically viable alternative based on multiple heat sources and cogeneration, which can reduce price risks [6]. As a result, some German states have already enacted legislation requiring them to engage in municipal heat planning processes [7] and a national regulatory framework may soon follow [8]. The city of Leipzig, the subject of this paper, has also committed to achieving a climate-neutral energy supply, including its local heating network, by 2038 [9].

In order to integrate the development in the German heating market described above into a scientific framework, this paper aims at answering the following research question: Which strategy for full decarbonization seems to be the most economically and technically feasible given the uncertainties in commodity prices. To this end, a general approach is taken by comparing different technological solutions based on their economic viability. A case study for the city of Leipzig is conducted, aiming at general applicability.

II. Literature review

This paper analyzes a variety of scientific publications to identify approaches, drivers, and barriers for a climate-neutral transformation of the district heating system. The publications are divided into two groups: First, studies on Germany are evaluated to gain an understanding of the technical, socio-economic and regulatory framework for the case study. Second, the European state of the art is outlined based on peer-reviewed case studies.

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A. *District heating in Germany*

One metastudy for the German energy system addresses the potential, costs and implementation of a climate-neutral transformation [10]. Scenarios from several studies [11–16] are considered and possible developments for the heating sector are elaborated. Furthermore, technologies and support programs for a climate-neutral transformation are evaluated with regard to their effectiveness. The focus of [17] is on the regulatory framework, which is examined using the example of six German municipalities of different sizes in two scenarios each towards a climate-neutral heating system. Based on the observed barriers and opportunities, a new holistic regulatory framework is designed by extending or deconstructing the existing framework. In [18], a scenario-based analysis of the transformation path for the German energy system in the European context is performed. The scenarios represent different policy development assumptions regarding subsidies and regulatory frameworks and consider different generation technologies. The study follows a dual approach: a macro perspective on the energy system as a whole and a micro perspective on smaller individual cases and their interactions are investigated. The results are specific DH generation costs for the considered microsystems as well as an economic impact assessment from the macro perspective.

All of the studies reviewed emphasize the critical role of DH technology in decarbonizing the heating sector, especially in urban areas. The above studies recommend a combination of approaches to facilitate the decarbonization of DH. These approaches generally include the integration of renewable energy sources (RES) such as geothermal, solar thermal, and biomass; the use of surplus industrial heat; thermal energy storage (TES); and the electrification of heat generation through heat pumps and direct power-to-heat (P2H) technologies. In addition, lowering the operating temperature of DH systems is a possible measure for integrating low-temperature heat sources. While [10] argues for more intensive use of combined heat and power (CHP) to efficiently integrate the intermittent nature of RE, [18] sees CHP only as a bridging technology. One publication points out the typically fossil fuel nature of CHP, which contradicts the original goal of decarbonization, and proposes phasing out the relevant subsidies [17]. The studies find that the current regulatory framework, made up mainly of the Combined Heat and Power Act (*Kraft-Wärme-Kopplungsgesetz*, KWKG), Buildings Energy Act (*Gebäudeenergiegesetz,* GEG), Fuel Emissions Trading Act (*Brennstoffemissionshandelsgesetz*, BEHG) and the Federal Funding for Efficient Heat Networks (*Bundesförderung effiziente Wärmenetze*, BEW) is suboptimal. It is suggested that the existing regulatory framework leads to difficulties in long-term planning for relevant stakeholders In addition, [17] points out that wrong incentives are set, e.g. by the KWKG, which promotes fossil CHP plants, or by the current methodology of the energetic evaluation of heat grids using the electricity credit method. In [10] it is also pointed out that the CO2 price set by the BEHG is currently not high enough to meet the 2030 targets. Finally, the regulatory framework has to be adjusted to financially incentivize the expansion of a decarbonized DH system and investment in and operation of large-scale heat pumps [18].

B. *District heating in European countries*

The analyzed European state of the art for DH systems revealed trends similar to the German studies. While some publications give an insight into the state of DH systems in general [19, 20], low-temperature DH-systems are discussed in references [21–23], and barriers and opportunities for decarbonization in references[24, 25]. More specific aspects of DH systems are also analyzed, like excess heat integration [26] and Smart Asset Management [27]. The integration of renewables is seen as a necessary precondition for decarbonization, but it is not enough to arbitrarily integrate intermittent RES, as noted by [28]. For example, in one case considered large shares of solar heat lead to an increase in emissions. Therefore, the focus should be put on sensible decarbonization measures. [29] suggests the integration of controllable CHPs to cover possible demand deficits, others [21, 28, 30] rely on TES to meet the demand and [31] even suggest the utilization of Demand Side Management (DSM) to ensure system stability. Excess heat is also considered as a valuable resource for DH systems [26] and can supply a significant share of the heating demand. Additionally, some studies [32, 33] suggest the use of renewable DH systems in rural areas, e.g. a combination of geothermal heat sources with long-distance heat transport. The operation as an energy community to minimize DH demand is suggested by [34]. In conclusion, a combination of RES and TES integration, heat electrification, excess heat utilization, and operation temperature reduction is recommended to achieve climate neutral transformation of the DH system.

C. *Contribution*

The novelty supplied by this paper is the investigation of several holistic, fundamentally different approaches to full decarbonization of an entire DH system. This is done through cost optimization of techno-economical energy system models. The modelled scenarios are thereafter technically and economically assessed and compared.

III. MATERIAL AND METHODS

The methodological approach chosen for this study is discussed in the following section and displayed in

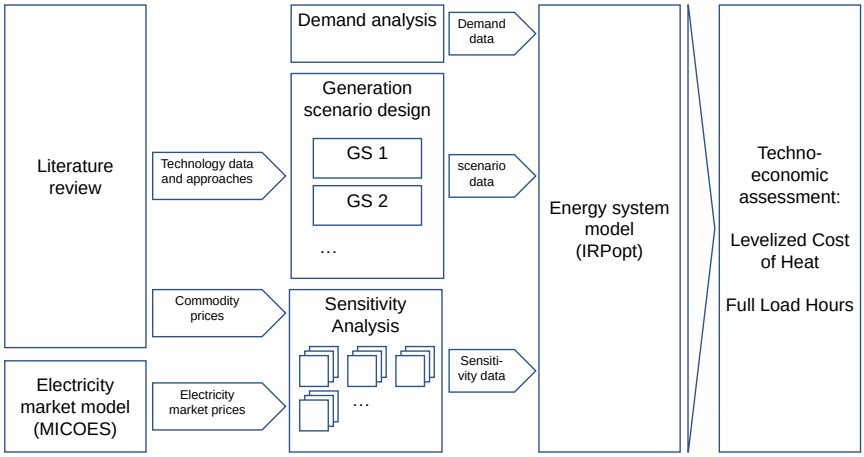

Figure *1*.

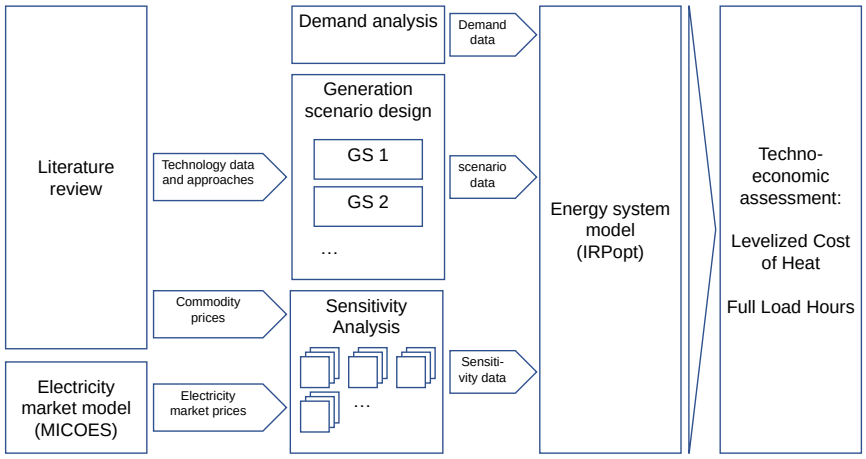

Figure 1. Methodological approach for the paper as a graphical abstract

A. Demand analysis and generation scenarios

1) Demand analysis:

It is expected that the DH's share of Leipzig's total heat demand will exceed the current 30% as the system continues to expand. On the other hand, efficiency improvements for buildings and DH systems incentivized by legislature such as GEG and BEW will lead to a decrease in total heating demand. In total, the cumulated annual demand for DH of Leipzig for 2040 is assumed to be approx. 1651 GWh, with a maximum load of 550 MW during the heating period. The remainder of the total heat load of Leipzig is outside of the scope of this study.

2) Generation scenario design:

For the post fossil future, a variety of four different technology development paths – hereafter called generation scenarios (GS) – are investigated. The generation scenarios all take different approaches to cover the DH demand contained in the network. They are extreme approaches as they only focus on one or a few different technology options. A detailed overview of the generation scenario design can be found in TABLE A I and Figure A 1 in the Appendix while a short overview is given at this point:

- GS 1: Natural gas with Carbon Capture and Storage (CCS) and carbon neutral bio methane
- GS 2: Hydrogen from regional sources or (inter)national markets
- GS 3: Mix of biomass, waste heat and solar thermal
- GS 4: Focus on electrification of heat supply

Most technical and economic assumptions regarding the CCS-technology of the first portfolio stem from [35]. Three large scale CHP plants supply the base load of heating from natural gas with post combustion CCS, with a smaller block engine and heating plant fired by renewable bio methane as peak load. As the Carbon Capture process only captures around 90 % of the CO_2 in the power plant's flue gas, 10 % of the fuel for the large CHP plants is provided as bio methane, to ensure a carbon neutral heat generation. In the second scenario, hydrogen is used for large scale CHP-production and heat plants in combination with an industrial heat pump using an electrolyzers as a heat source. The hydrogen will stem from (inter)national markets or regional RES overproduction. For the third portfolio a diversified approach is applied. Biofuels (biomass and bio methane), waste (Waste-to-Energy and industrial waste heat), heat pumps and solar thermal are utilized in a variety of power plants. The fourth and last portfolio focuses on supply through power-to-heat-technology (heat pumps from various heat sources and electrode boilers). However, a bio methane block engine and industrial waste heat is also part of this portfolio. For all generation scenarios, the possibility to sell or buy heat at disadvantageous rates exists (sales price -1 EUR/MWh; purchase price: 500 EUR/MWh), mostly to avoid unsolvable model constellations.

B. Sensitvity analysis

As the current Energy crisis in Europe most recently shows, commodity prices exhibit high insecurity. In order to take into account possible fluctuations in commodity prices toward 2040 a sensitivity analysis is applied in this study. The base prices for the commodities are used for the reference cases and are extracted from the studies considered in the literature review. While the base price describes the most likely value the prices are expected to assume, their

respective sensitivities are potential deviations that may occur in the future. Base prices as well as sensitivities are presented in TABLE I.

Commodity	**Price in EUR/MWh (incl. sensitivities)**			**Generation scenario influenced by**
Biomethane			**163.75**	
Waste			**-19.60**	
Natural gas	**25.00**	50.00	100.00	GS 1
Electricity	**33.89**	51.20	79.36	GS 1, GS 2, GS 3
Biomass	**25.00**	50.00	100.00	GS 2
Hydrogen	**50.00**	100.00	200.00	GS 3

TABLE I. COMMODITY PRICES: BASE PRICES AND SENSITIVITIES, REFERENCE CASE VALUES IN BOLD PRINT

Not all sensitive values have an impact on the considered generation scenarios. The generation scenarios are only influenced by one or two of the four sensitivities. The GS that are being influenced by the respective sensitivities are displayed in the rightmost column of TABLE I.

C. Model framework

Part of the paper's methodology is the application of two energy system models that have been developed at the Institute for Infrastructure and Resources Management (IIRM) at Leipzig University. MICOES (Mixed-Integer Cost Optimization of Electricity Systems) is applied upstream to model European power market scenarios and a resulting electricity price at an hourly resolution. Extended documentation on this model is given in [36, 37]. All generation scenarios and their sensitivities are then fed into the energy system model IRPopt to compute a cost-minimal economic dispatch. IRPopt (Integrated Resource Planning and Optimization) is an integrated multi-modal energy system model [38–41]. It is used to match energy flows between energy demand and energy source. With the bottom-up techno-economic numerical optimization model, that is implemented in GAMS/CPLEX, it is possible to solve mixed-integer problems down to a quarter-hourly resolution for multi-annual periods. While the model has been applied for different case studies at different spatial levels [42–44], the energy systems modelled for this study are shown in Figure A 1.

D. Assessment

Finally, the economic dispatch modelled by IRPopt based on generation scenarios and sensitivity analysis is technically and economically assessed. To that end, some relevant Key Performance Indicators (KPIs) have been chosen and defined for the case study at hand. Technical KPIs are the Full Load Hours (FLH) and the heat output of the generation plants. A plants FLH is calculated by dividing the (expected) annual energy output by its nominal power.

The KPI for the economic assessment is the LCOH which is a useful method for comparing and benchmarking technology mixes with different cost structures and operating lifetimes [45]. The LCOH is composed of the annualized investment, annual fixed and variable operation and maintenance costs, annual energy costs and annual revenue divided by the annual useful heat demand.

IV. RESULTS

This section presents the technical and economic assessments of the modelling results regarding the generation scenarios and the sensitivity analysis.

A. *Assessment of the reference case*

First, a reference case for each of the four generation scenarios is considered and assessed in detail with the corresponding commodity price data shown in bold in TABLE I. The modelling results and assessment are presented in TABLE II, the technical details of the generation scenarios are displayed in the first four rows and specific cost components and the LCOH are displayed in the last four rows.

		Unit	GS 1	GS 2	GS 3	GS 4
	Produced heat	GWh	1671.78	1656.35	1956.55	1755.62
	Excess heat	GWh	15.51	1.45	300.07	84.24
	Heat deficit	GWh	0.00	1.33	8.05	1.18
	FLH	h	4710.98	4717.62	5837.00	3265.64
specific	Annual variable and O&M costs	EUR/ MWh	117.76	73.47	37.12	61.84
specific	Annualized investment costs	EUR/ MWh	58.51	35.18	43.61	18.75
specific	Annual revenue	EUR/ MWh	37.60	16.99	7.02	0.12
	LCOH	EUR/ MWh	138.67	91.65	73.71	80.47

TABLE II. RESULT OVERVIEW OF THE GENERATION SCENARIOS' REFERENCE CASES

The FLH of the generation scenarios are calculated as weighted average of the FLH of all installed plants (weighted by their respective heat production), thereby providing an indication of the utilization of the respectively installed capacity. For the reference case it is highest for the GS 3. The produced, excess heat and heat deficit on the other hand give an indication of the adequacy of the installed capacity – how much excess heat needs to be sold off? – and the concurrence of supply and demand – how much heat needs to be purchased to cover shortfalls? The produced heat, minus the excess heat and losses, plus the heat deficit, gives the annual demand of 1651 GWh. Accordingly, some details can be extracted upon closer inspection. In GS 1 (Natural gas and CCS), the CHPs are operated at times of high electricity prices, even if no DH demand exists. The excess heat is then sold at a disadvantageous price. In generation scenario 3, a lot of excess heat is produced and sold off. Here, a conflict of interest between a solar thermal plant, a waste incineration plant and industrial excess heat all feeding into the DH system at low generation cost result in a large surplus of heat. The TES – which is installed in all generation scenarios – is used much more in the latter GS (3 and 4) with an industrial waste base load producing excess heat in the warmer season (and intermittent RES in the case of GS 3), than in the former GS (1 and 2) with controllable generation plants.

The costs and revenue structure is diverse. The LCOH are equal to the sum of costs minus revenues. Revenues are generated exclusively from the sale of electricity produced by CHP plants. As these generation plants predominate the two former GS, larger revenues can be found in GS 1 and 2 (38 and 17 EUR/MWh) than in GS 3 and 4 (7 and 0 EUR/MWh).

A relatively large spread can be identified for the specific investment costs (19-59 EUR/MWh). In particular, GS 1 is characterized by high investment costs due to the high cost of retrofitting carbon capture technology. The GS 4, on the other hand, stands out by the lowest investment cost, as the deployed heat pump and P2H technology used cost less initially. However, the variable cost of electricity (in particular including grid utilization fee and other levies) is relatively high and leads to comparatively high variable cost of 62 EUR/MWh. However, the fuel cost of hydrogen and natural gas lead to even higher variable costs of 73 and 118 EUR/MWh, respectively. The resulting LCOH show a large range from 74 to 139 EUR/MWh.

B. Assessment of the sensitivity analysis

The approach taken to show the impact of the sensitivity analysis is the following: The change in commodity prices based on the sensitivity analysis is shown on the x- and y-axis of the bubble charts in Figure 2, while the LCOH resulting from each sensitivity is represented by the area of and the number shown in the bubble.

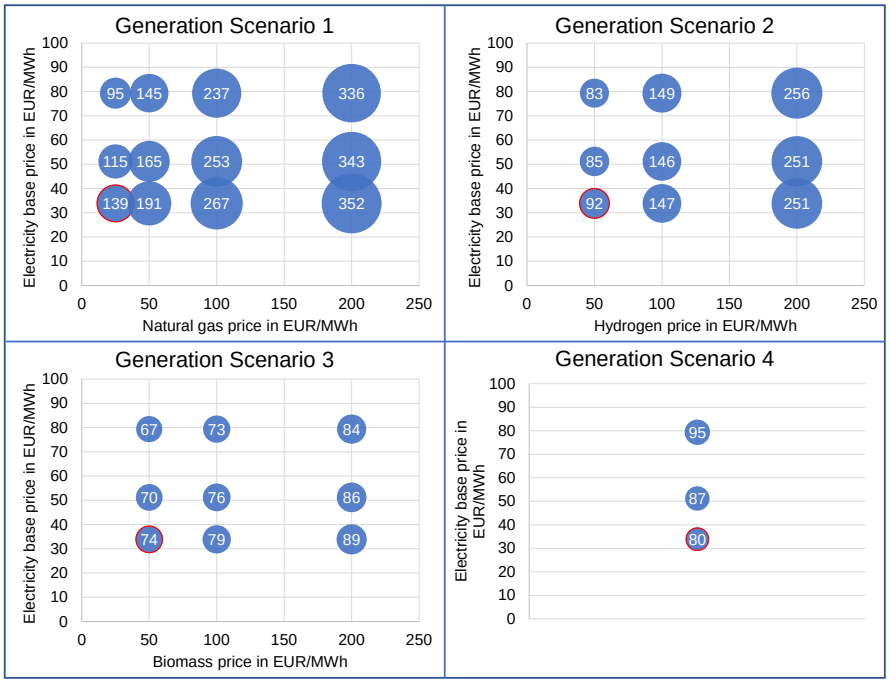

Figure 2. Effect of the sensitivity analysis of commodity prices on the LCOH, the reference case is framed red (LCOH values given in the bubbles in

An increased volatility and higher average of the electricity price (see Figure A 2) mostly leads to a decrease of the LCOH. This effect is visible for GS 1,2 and 3, where electricity is sold by the CHP plants. Higher and more volatile prices lead to higher revenue and therefore lower LCOH. In contrast, in GS 4, where electricity is mainly used to fuel heat pumps and electrode boilers, an increase in electricity price raises the LCOH. Interestingly, the impact of higher electricity price volatility vanishes for larger hydrogen prices (200 EUR/MWh) in GS 2. This is due to a weaker utilization of the hydrogen turbines and a stronger utilization of P2H-technologies for high hydrogen prices. The corresponding shift from electricity production to consumption leads to stable LCOH over variable electricity cost. Increasing the price for natural gas in GS 1 results in a shift in the balance between imported and exported heat. Larger amounts of heat are imported and smaller amounts exported, as the price for natural gas rises. This is because an import of heat becomes more economically in comparison to heat production using natural gas and export of excess heat. As GS 3 is a fairly well diversified generation scenario using biomass, electricity, solar and excess heat, changes in respective fuel prices (electricity and biomass) have a less pronounced effect on the resulting LCOH of this generation scenario. A similar correlation can be seen in GS 4, which is also more diversified in terms of the utilized fuels (electricity, excess heat, bio methane) than the first two GS.

V. Discussion

According to [35], plants being retrofitted with CCS technology should run as stable as possible to avoid overloading the carbon capture process. Specifically, natural gas-fired CHP plants should optimally not exceed a number of ~30 starts per year. However, this number is exceeded by far in the CCS scenario at hand. Some municipalities are questioning whether the integration of natural gas-fired CHP plants with CCS into the DH systems is a viable option. According to our research, there is currently no economic perspective as other options appear to be more viable. Multiple studies [17, 18] state that hydrogen should not be used in the heating in buildings to a large extend. Instead it should be utilized in other sectors like the steel and chemical industry, where a decarbonization is much costlier otherwise. If at all, it should make a marginal contribution to the heat generation. Nonetheless, its applicability was tested in GS 2 and ruled out based on its economic inefficiency in comparison to other scenarios.

Another important fact, that is partly neglected in this paper's framework is the question of DH infrastructure (pipelines, substations, pumps, etc.). The investment and operation cost of this infrastructure is mostly neglected. This is due to the fact that it can be considered an offset, that is very similar for all generation scenarios under consideration, as the DH demand development assumptions are the same for all scenarios. One large infrastructure investment that

is explicitly considered in GS 3 and 4 is the pipeline connection between the industrial site and Leipzig's DH system for the industrial excess heat [46]. Although the offset can be neglected when comparing generation scenarios among one another, it makes comparison with other studies and publications more difficult.

The scenarios considered in one German case study [47] lead to LCOH of 140 to 165 EUR/MWh, for one particular scenario largely supplied by heat pumps. The authors critically comment on high levies and fees for electricity powered heat pumps, impeding their economic feasibility. The results of this study support that comment, as a major part of the variable cost of GS 4 originates from the electricity levies and fees, making it less efficient than it could be. Another German case study [32] finds LCOH in a range of 20 to 85 EUR/MWh, the last one being the final DH customer price of Munich and the former being biomass or electricity based scenarios. The LOCH of the reference cases of GS 2, 3 and 4 seem to be in similar ranges to the current supply cost of Munich's DH system, implying, that the decarbonization of DH systems may be possible without too much additional investment. However, infrastructure investments are not considered in this study and the comparability of Leipzig's and Munich's DH systems is uncertain, complicating a direct comparison of the LCOH. A Finnish case study [28] calculates LCOH between 32 and 55 EUR/MWh for the integration of solar heat and TES into DH systems, while a Swiss case study [48] finds LCOH between 195-325 EUR/MWh for biomass, geothermal and electricity powered scenarios. Depending on the respective DH system conditions and the investigated scenarios, a wide range of LCOH can be found in recent publications. The utilization of the TES is higher in generation scenarios with intermittent RES than in those with controllable generation plants. Also, the conflict of interest between solar thermal plant, waste incineration plant, and industrial excess heat in GS 3 leads to a large excess of heat. This suggests the need for policies that incentivize technology for the integration of different types of heat sources (e.g. TES or DSM) into the DH system, especially for renewable energy projects. Furthermore, the sensitivity analysis shows that increased volatility and higher average electricity prices lead to lower LCOH in electricity generation scenarios (GS 1,2 and 3; see Figure 2). This indicates the need for policies that promote the development and deployment of technology with high flexibility, such as TES and DSM technologies, to help mitigate the impact of price volatility. In future research, more generation scenarios should be inspected to gain a deeper insight into the effect of diversification of generation technologies. As the most diversified scenario with the lowest LCOH, GS 3 demonstrates the positive impacts that diversification can have.

VI. Conclusion

The study provides a good general overview as well as some interesting highlights regarding the transformation toward carbon neutrality in the DH sector. Four distinct generation scenarios for a full decarbonization of the DH system are designed. LCOH and operating hours for the generation scenarios and various sensitivities are derived from a techno-economic model. The LCOH range from 74 (diversified scenario, GS 3) to 139 €/MWh (natural gas scenario, GS 1) for the reference cases. By increasing the fuel prices, the sensitive impact on the LCOH varies greatly (see Figure 2). While the LCOH for GS 1 and 2 may increase by more than half of the initial parameter increase, only a marginal increase can be seen in GS 3 and 4. In terms of generation technologies, it becomes clear that under current assumptions a reliance on natural gas or hydrogen alone is not an option. Instead, diversification measures have to be taken to mitigate commodity price risk. Overall, the results suggest the need for a comprehensive policy framework that supports the transition to a low-carbon and efficient heat generation system, that incentivizes the adoption of renewable energy sources, that promotes the integration of different types of heat sources, and that supports the development of energy storage and demand response technologies.

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APPENDIX

TABLE A I: OVERVIEW OF THE GENERATION SCENARIOS

Generation scenario	**1**			**2**			**3**			**4**		
Name	***Gas + CCS***			***Hydrogen***			***RES mix***			***Power-to-heat***		
Assumptions	Natural gas supply at low cost CCS infrastructure available			Hydrogen imports for district heating			Diversified use of biomass, waste heat, and solar			Focus on electrification of heat supply		
	Primary energy	Conver-sion type	Capacity (MW_{th})	Primary energy	Conver-sion type	Capacity (MW_{th})	Primary energy	Conver-sion type	Capacity (MW_{th})	Primary energy	Conver-sion type	Capacity (MW_{th})
Heat generation plants	Natural gas	Gas OCGT	150	Hydrogen	Gas OCGT	300	Bio gas	Gas OCGT	150	Bio gas	Block engine	15
		Gas CCGT	200		Block engine	15	Bio mass	Steam turbine	25	Industrial waste heat	Heat exchanger	100
	Bio gas	Block engine	35	Electr/Waste heat (medium)	Heat pump	100	Waste	Steam turbine	25	Electr/Waste heat (medium)	Heat pump	50
							Industrial waste heat	Heat exchanger	100	Electr/Waste heat (low)	Heat pump	50
							Electricity/ Waste heat (medium)	Heat pump	50			
	Bio gas	Heat plant	130	Hydrogen	Heat plant	100	Bio mass	Heat plant	45	Electricity	Power-to-heat	200
		Heat storage	135		Heat storage	135		Heat storage	135		Heat storage	235
							Solar	Thermal plant	120			
Total			***650***			***650***			***650***			***650***

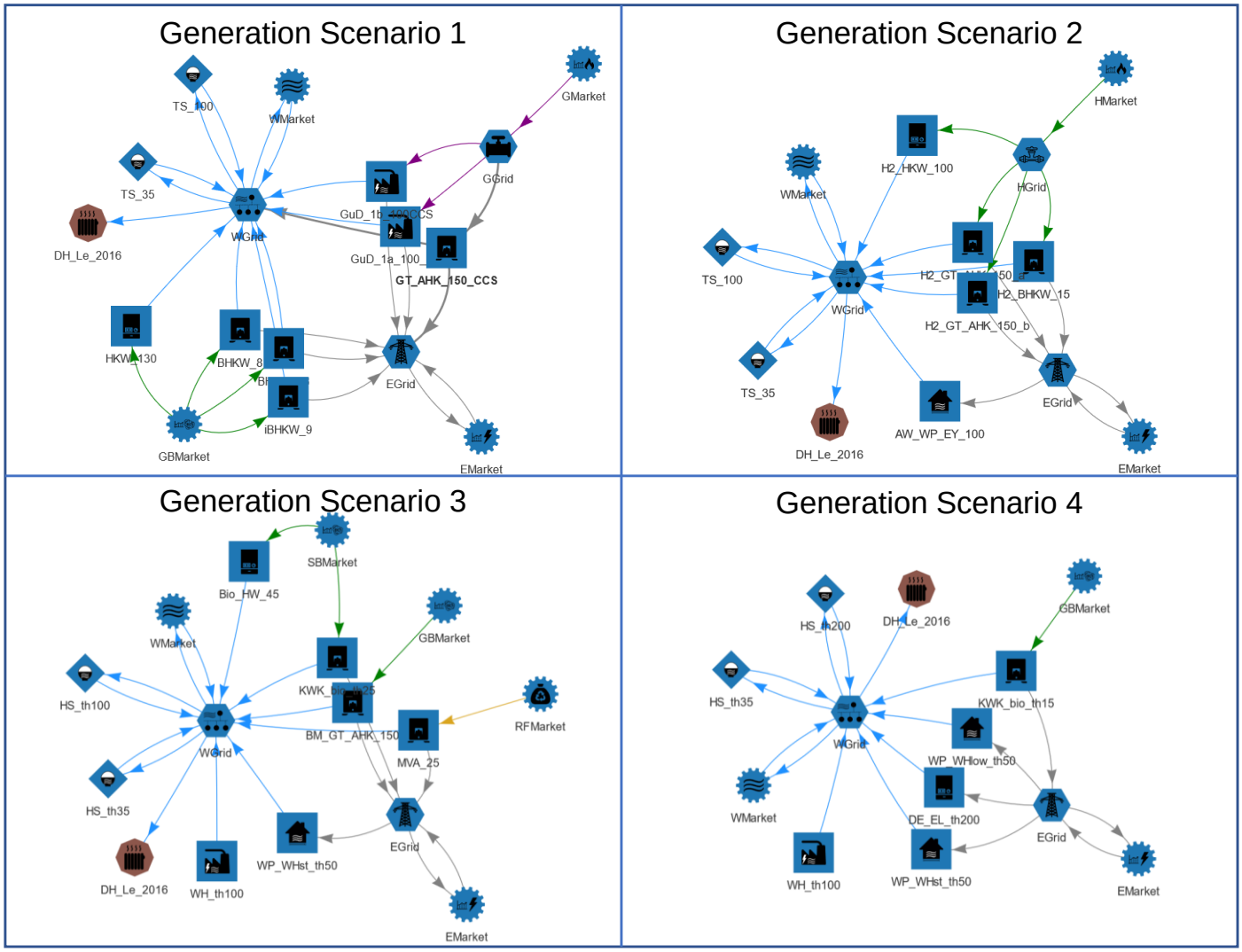

Figure A 1. Implementation of generation scenarios in IRPopt

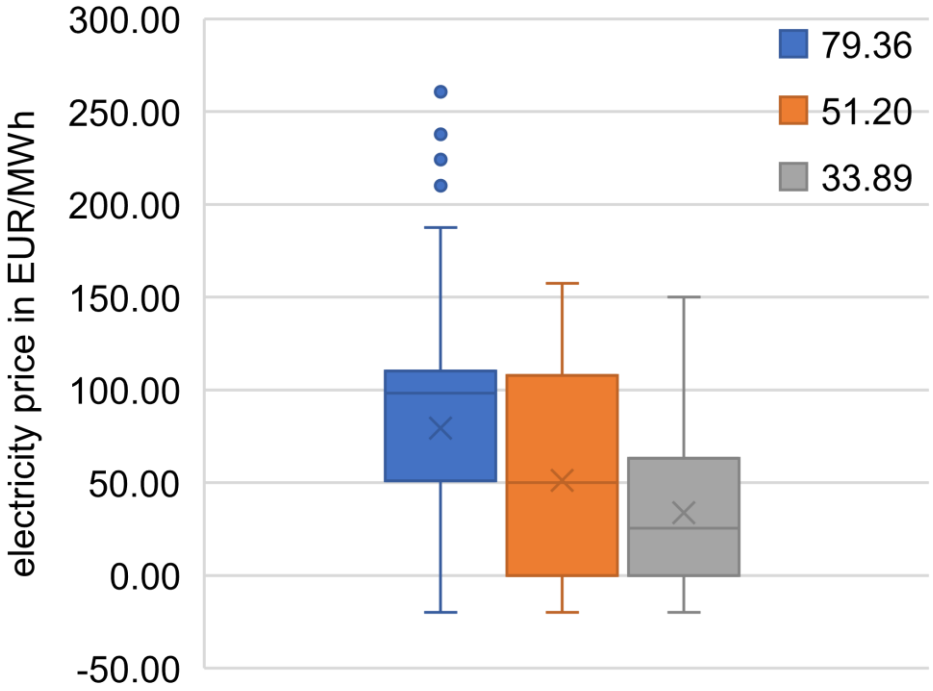

Figure A 2. Distribution of electricity prices for the considered sensitivities, source: MICOES; IIRM