Sector coupling technologies in gas, electricity, and heat networks

Competition or synergy?

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Current investment in distribution networks for electricity, gas, and heat is high, and the distribution networks play a prominent role in the necessary transformation of the energy system. This paper provides insights into the relationship between residential end-user decisions on heat supply and their effect on infrastructure planning. Therefore, the gas, electricity, and heat networks are analyzed together. After a review of the characteristics of the networks, the most common sector coupling technologies are compared economically and environmentally. The results show that, under the assumptions made, heat pumps are the cheapest option for residential end-users in the long run. This raises the question of whether a parallel development of three different infrastructures for the heat supply of buildings is the best path to a successful energy transition.

Sektorkopplungstechnologien in Gas-, Strom- und Wärmenetzen
Konkurrenz oder Synergie?

Die derzeitigen Investitionen in die Verteilnetze für Strom, Gas und Wärme sind hoch und die Verteilnetze spielen eine bedeutende Rolle bei der notwendigen Transformation des Energiesystems. Diese Arbeit gibt Einblicke in den Zusammenhang zwischen Entscheidungen privater Endnutzer zur Wärmeversorgung und deren Auswirkungen auf die Infrastrukturplanung. Dafür werden die Gas-, Strom- und Wärmenetze gemeinsam analysiert. Nach einem Überblick über die Charakteristika der Netze werden die gängigsten Sektorkopplungstechnologien ökonomisch und ökologisch verglichen. Die Ergebnisse zeigen, dass unter den getroffenen Annahmen Wärmepumpen langfristig die kostengünstigste Option für private Endnutzer sind. Dies wirft die Frage auf, ob eine parallele Entwicklung von drei verschiedenen Infrastrukturen zur Wärmeversorgung von Gebäuden der beste Weg hin zu einer erfolgreichen Energiewende ist.

Keywords: *gas network, electricity network, heat network, end-user perspective, infrastructure planning*

Introduction

The national and international commitments to curb greenhouse gas (GHG) emissions (UNFCCC 2015; BMU 2016) make the reduction of fossil energy sources to a minimum by 2050 a necessity. Achieving this requires a fundamental transformation of not only the energy sector, but also changes in the demand sectors of households, transport, trade, commerce, and services (TCS), and industry.

With a share of 23.8 % in Germany in 2017 (AGEB 2018), natural gas is the second most important primary energy source after mineral oils. Natural gas is also used as a final energy source in almost every sector. Only in the transport sector is it less relevant with minor market shares of natural gas-powered passenger cars. However, there is a growing focus on alternatives, especially regarding buildings (households and TCS). For example, heat pumps are increasingly used to supply heat to highly insulated buildings and are being installed in heat networks (district heating).

Various studies, investigating a significant GHG reduction of 95 % until 2050 compared to 1990, indicate a clear decline in the demand for natural gas by 2050 (dena 2018; BCG and prog-

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nos 2018; Öko-Institut and Fraunhofer ISI 2015). These studies point to a move from heat generation based predominantly on natural gas to electricity-based heat by 2050, especially concerning buildings. Such a strong drop in the demand for natural gas in a gas distribution network, assuming its size remains unchanged, results in a sharp rise in the specific operating costs (Wachsmuth et al. 2019) and casts doubt on the economic efficiency of a natural gas distribution network for supplying heat to buildings.

To analyze the competitive situation of the natural gas distribution network, the gas, electricity, and heat distribution infrastructures are analyzed together. The definition of sector coupling is broadly discussed in the literature (Wietschel et al. 2018 b; Scorza et al. 2018; bdew 2017). We understand sector coupling as the linking of the sectors electricity and heat with their infrastructure, i. e. a stronger coupling of the grid-bound energy sources electricity, heat and gas. The technologies, that couple the networks with each other, differ depending on the demand sector. We will focus on the building sector. In this sector, gas boilers and to a limited extent combined heat and power plants (CHP) are connected to the natural gas distribution network. The electricity distribution network supplies heat pumps and electric heating appliances as well as night storage heaters, the latter to a limited and declining extent. Alongside oil-based options, these compete with gas boilers and heat networks to supply buildings with heat. A strong synergy emerges between the electricity distribution network and heat networks if the latter are supplied with heat from large heat pumps or electric heating rods. Otherwise, when using geothermal or solar thermal technologies as a heat source, the heat networks compete with natural gas and electricity distribution networks to supply heat to buildings.

The objective of the paper is to provide insights into the connection between residential end-user decisions and their potential effect on infrastructure planning. These insights then contribute to the question of the role to be played by the gas distribution network in the energy system of the future. As a first step, the characteristics of the three infrastructures and the current regulatory framework are described and the most relevant sector coupling and competing options are pointed out. Subsequently, an economic comparison and a comparison based on CO_2 emission of those technologies in Germany is made, to provide insights into the basis of decision-making for residential end-users, and the results are explained.

Perspective of network operators: characteristics of the infrastructures

The annual investment and service and maintenance expenses of gas and electricity distribution networks are nearly double the expenses of their transport networks, so that infrastructure changes will lead to higher expenses on the distribution network level than on the transport network level. Comparing the investments per kilometer expanded in electricity and gas distribution networks reveals that specific investments in electricity (624,584 €/km) are much higher than in gas (90,162 €/km) (BNetzA and Bundeskartellamt 2019). The cost of building heating networks is 50,000 €/km under very favorable conditions and can be up to 800,000 €/km under unfavorable conditions (for example in dense urban areas) (Clausen 2012). On the other hand, the service and maintenance expenses for the total length of the distribution networks are significantly higher for the gas distribution network, with 2,105 €/km, than for the electricity grid, with 1,734 €/km. Furthermore, the energy transported via the gas distribution network was 754 TWh in 2018. This is considerably more than via the electricity distribution grid, which was only 443 TWh (BNetzA and Bundeskartellamt 2019).

The expansion and maintenance of the gas and electricity distribution networks is planned and implemented by the respective distribution network operator (DSO) separately, according to the amount of energy purchased in a network area. This is done due to the link between rising costs and decreasing demand. For example considering the situation for gas distribution networks, there is a clear increase in the specific operating costs if the length of the gas network remains the same but there is a drop in the demand for gas.

So-called network charges distribute the costs for building, operating, maintaining and expanding the gas and electricity networks across all network users (BNetzA and Bundeskartellamt 2019). Broadly speaking the higher the utilization of electricity or gas networks is, the wider the cost can be spread among network users; a lower rate of utilization of the infrastructure leads to higher individual costs for the remaining network users. With a 22.3 % share of the German average electricity price of 30.85 €ct/kWh, the electricity network charges for transportation and distribution networks have a similar share of prices to those of the gas network charges, which account for 23.3 % of the average German gas price of 6.34 €ct/kWh for household customers (BNetzA and Bundeskartellamt 2019). However, at nearly a quarter of the price, the network charges, and consequently the infrastructure cost, have a strong influence on the end-user price.

Perspective of residential end-users: sector coupling and competing technologies

Since the distribution network level is of particular importance, we focus on heat supply in the residential building sector. In particular, the technologies with the highest relevance – gas boilers, heat pumps and a connection to a heat network supplied by a large heat pump – are considered in more detail. BDEW (2019) shows that user satisfaction is highest with these selected technologies.

Efficient gas condensing boilers are the current state-of-the-art technology capable of achieving an efficiency of more than 90 % (Hirzel 2017). With a view to decarbonization, a move from natural gas to synthetic methane, produced using electricity, by 2050 is being discussed. Synthetic methane can be fed into the gas distribution network without any additional modifications and can be used to fuel condensing boilers (Viebahn et al. 2018). Condensing boilers are promoted in Germany by the nationwide funding offered by the Kreditanstalt für Wiederaufbau (KfW) and the Federal Office for Economic Affairs and Export Control (BAFA). The KfW funds the conversion of gas heating systems to condensing boiler technologies with low-interest loans of up to € 50,000 or with subsidies of 20 %, which can range between € 300 and € 10,000 (KfW 2020). BAFA funds up to 20 % of the eligible costs of converting an existing boiler to a condensing one if solar thermal is installed as well (BAFA 2019).

The sales figures for heat pumps in Germany show that electricity-based air heat pumps are currently preferred (BWP 2019). The efficiency of such a system is measured using the so-called annual coefficient of performance (COP), which represents the ratio between the amount of heat supplied and the amount of power used (Wietschel et al. 2018 a). The COP of such devices depends heavily on the heat source used and is on average around 3.0 for air heat pumps (Miara et al. 2011). To ensure their efficient operation, the temperature difference between the heat source and the heating system should be as low as possible, which is why its performance is best in well-insulated buildings (Wietschel et al. 2018 a). BAFA funds heat pumps through the KfW mainly via loans with a repayment bonus or investment subsidies for energy-related (complete) renovations (BWP 2020). For air heat pumps this funding is 45 % of the eligible costs when substituting oil-based heating in existing buildings and 35 % when replacing a different kind of heating system. The required COP of the heat pumps is ≥ 3.8 (BWP 2020). For new buildings, the funding is also 35 % of the eligible costs, but the required COP is ≥ 4.5 (BWP 2020).

Large heat pumps installed in heat networks function in a similar way to other heat pumps. As a private person, a subsidy for establishing a connection to a district heating network can be granted in Germany under the KfW subsidy program No. 430. A subsidy of 10 % is granted up to a maximum amount of € 5,000 per housing unit (KfW 2019).

Comparison of sector coupling and competing technologies

To provide a clearer picture of the possible heat production options for residential end-users this section compares the sector coupling technologies described above using a defined case study regarding environmental and economic aspects. The analysis includes the different framework conditions of single-family houses (SFH) and multi-family houses (MFH) in existing buildings and new buildings for 2015 and 2050. The economic analysis also considers the current funding possibilities. It is assumed that these subsidies will no longer apply in 2050. Further the comparison is based on useful energy. This is the part of energy that is left after converting the final energy, such as electricity or natural gas, into – for example – light or heat.

The existing SFH considered has a floor area of 140 m² and currently a heating demand of 236 kWh/m² and therefore an annual heating demand of 33,040 $\text{kWh}_{\text{useful energy}}$ (dena 2016). In 2050 the existing SFH assumed has a heating demand of 40 kWh/m², because the buildings newly constructed in 2015 will be the existing buildings in 2050. A newly built SFH has an annual heating demand of 5,600 $\text{kWh}_{\text{useful energy}}$ for the same floor area in 2015 and 2050 (dena 2016). The MFH is assumed to be a five-story building with two apartments per story, each with a floor area of 80 m². This results in a heating energy demand of 132,800 $\text{kWh}_{\text{useful energy}}$ per year for existing buildings in 2015 and 32,000 $\text{kWh}_{\text{useful energy}}$ per year in new buildings in 2015 and 2050 as well as in existing buildings in 2050. These cases are only examples of current buildings. The structure of buildings and therefore their heating demand varies very widely. This is the case in both new buildings and existing buildings. Heating demand can range from below 100 kWh/m² to more than 500 kWh/m² (Häupl et al. 2017). These examples only represent conditions in a "typical" building and are taken from the dena report on buildings in Germany (dena 2016).

Economic perspective: costs, prices, and taxes/duties

The economic comparison is conducted from the point of view of the residential end-user and therefore shows which technologies are the cheapest solution for him/her. Tab. 1 provides an overview of the assumed investments and costs that are used to determine capital costs. With regard to funding, subsidies of 20 % are assumed for gas condensing boilers, 35 % for heat pumps, and 10 % for heat networks (see the section "Perspective of residential end-users: sector coupling and competing technologies"). For the existing buildings, it is assumed that the required heat pump COP of 3.8 cannot be achieved without an expensive (partial) refurbishment. Therefore, no subsidy is assumed for existing buildings and we consider a COP of 2.8.

For the operating costs of the different technologies, today's energy prices and the price development until 2050 are estimated based on various studies. The same studies show that for achieving a 95 % GHG reduction in 2050 compared to 1990, natural gas needs to be replaced by carbon-neutral synthetic methane (BCG and prognos 2018; dena 2018; Öko-Institut and Fraunhofer ISI 2015). The comparison for 2050 contains synthetic methane imported from North Africa. The Power-to-Gas and Power-to-Liquid (PtG/PtL) calculator of Frontier Economics (2017) was used to determine the costs for synthetic methane and 0.43 €ct/kWh was added for sales (Agora Energiewende and Frontier Economics 2017) plus another 10 % margin to obtain the price without taxes and levies. The assumed maintenance costs, as well as the efficiency developments of the technologies are based on Hirzel (2017), Viebahn et al. (2018) and Wietschel et al. (2018 a).

		Investment		Funding	Lifespan	Interest rate	Retrofitting costs	
		2015	2050	2015			2015	2050
		€	€	€	years	%	€/kWh	€/kWh
Gas condensing boiler	**SFH existing**	4,000	1,000	800	20	2	0.02	0.02
	SFH new	1,000		200			–	–
	MFH existing	15,000	4,000	3,000			0.02	0.02
	MFH new	4,000		800			–	–
Heat pump (air)	**SFH existing**	26,000	4,000	–	25	2	0.03	0.05
	SFH new	4,000	4,000	1,400			–	–
	MFH existing	106,000	20,000	–			0.03	0.04
	MFH new	25,000	20,000	8,750			–	–
Connection to heating network[1]	**SFH existing**	15,000		1,500	25	2	–	–
	SFH new						–	–
	MFH existing	40,000		4,000			–	–
	MFH new						–	–

[1] Expert interview on 24.01.2020

Tab. 1: Assumptions for the derivation of capital expenditures for the coupling technologies. *Source: Wietschel et al. (2018a), Clausen (2012), Henning and Palzer (2015)*

		Gas condensing boiler/gas		Heat pump/electricity		Connection to heating network/heat	
		existing buildings	new buildings	existing buildings	new buildings	existing buildings	new buildings
Efficiency in %	**2015**	90		280[1]	450[1]	100	
	2050			450[1]	450[1]		
Average energy carrier price for households (after-tax) in €ct/kWh	**2015**	6.3		21.7		8.9	
	2050	15.4		27.0		12.0	
Average energy carrier price for households (pre-tax) in €ct/kWh	**2015**	4.8		10.6		7.5	
	2050	5.3		13.1		10.1	
Price for synthetic methane (pre-tax) in €ct/kWh	**2050**	20.9		–		–	
Maintenance costs in €ct/kWh	**2015**	1.3		1.4	2.3	–	
	2050						

[1] As explained in the section "Perspective of residential end-users: sector coupling and competing technologies", the COP can be approximately defined as the efficiency. The COP represents the ratio between the amount of heat supplied to the amount of power used, which in turn means that it can be higher than 100%.

Tab. 2: Development of the efficiency of three sector coupling technologies and assumed price development of the four network-based energy carriers. *Source: Hirzel (2017), Viebahn et al. (2018), Wietschel et al. (2018a), dena (2018), BCG and prognos (2018), Öko-Institut and Fraunhofer ISI (2015), Agora Energiewende and Frontier Economics (2017), WIBERA (2017), BNetzA and Bundeskartellamt (2019)*

Tab. 2 provides an overview of the assumptions used to calculate the operating costs. The price of district heating up to 2050 was based on a linear extrapolation of prices according to WIBERA (2017). Comparing the difference of the average energy carrier price after taxes and pre-taxes shows the high tax burden on electricity compared to gas and heat.

Based on the assumptions described above, the capital and operating costs are calculated per kWh of useful energy (heat). Fig. 1 shows the results for investments and operating costs broken down by building category and technology. Operating costs are further split into on the one hand network charges and on the other hand other taxes, levies and charges. For SFH and MFH in new buildings the heat pump is already the most favorable solution today and continues to be so in 2050, with the expenditures in SFH being 18.4 €ct/kWh$_{\text{useful energy}}$ less than a connection to the heating network in 2050 and potential savings of 11.2 €ct/kWh$_{\text{useful energy}}$ for MFH. The specific costs of heat pump use in new buildings are lower than in existing buildings, as a higher COP can be achieved. For existing buildings, a gas condensing boiler running on natural gas is the cheapest technology option today, with only a difference of approximately 0.6 €ct/kWh$_{\text{useful energy}}$ compared to heat pumps. Connecting to the heating network is the most expensive solution for all building categories in 2015. In new buildings especially, the specific costs are significantly higher than for the other technologies, because the connection to the heating network leads to fixed costs and is not measured according to heating capacity.

Overall, the costs (excluding inflation) will increase in 2050 for all technology options. This is partly due to the rising energy carrier costs and partly due to subsidies no longer being available. Due to the high fuel costs the use of synthetic methane will not be competitive compared to the other heating technologies in 2050. For the network charges which include the infrastructure costs spread across the network users, the assumption is made that the share of network charges of the energy carrier price will stay constant until 2050, due to high uncertainties in their future development, leading to a slight increase in absolute network charges.

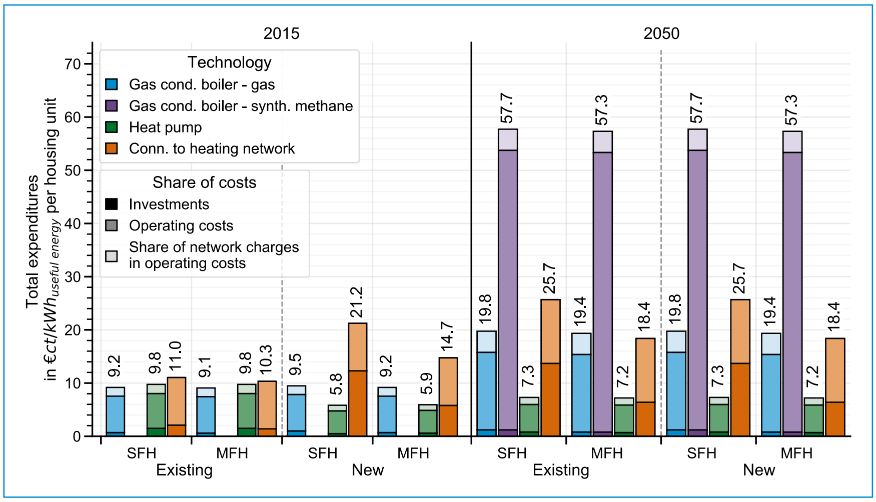

Fig. 1: Overview of the total expenditures for the different technologies in the different building categories.
Source: Authors' own compilation

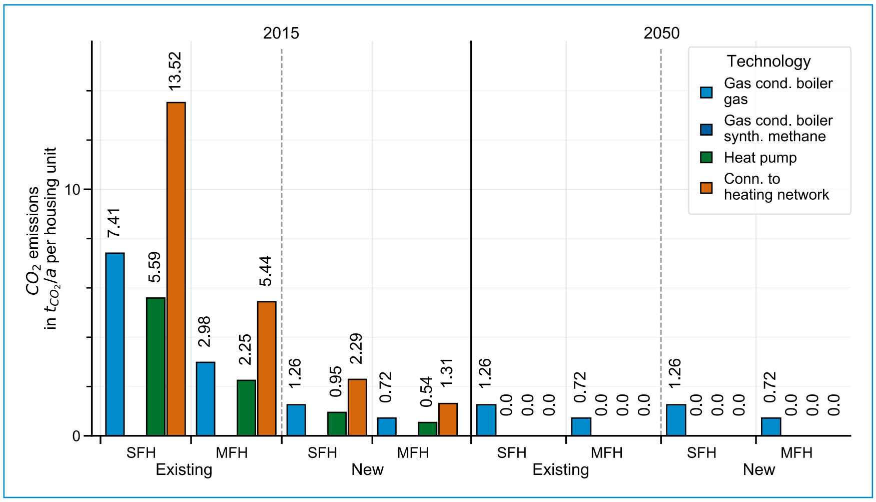

Fig. 2: Overview of the annual CO$_2$ emissions of the different technologies in the different building categories.
Source: Authors' own compilation

Environmental perspective: CO$_2$ emissions

To compare the environmental impact of the different technologies, an emission factor of 62.33 t_{CO2}/TJ$_{\text{useful energy}}$ is assumed for natural gas today and in 2050 (European Commission 2007). The current power mix is applied to heat pumps today (UBA 2019), and carbon-neutral electricity generation is assumed for 2050, without biomass and fossil fuels. GHG emissions caused indirectly or along the upstream, such as during the production of PV and wind power installations, are not considered. But their influence is negligible in a world with very ambitious climate protection measures. The emissions of district heating today depend on the heat mix fed into the networks (AGFW 2019). For 2050 it is assumed that the heat in heat networks is exclusively produced by large heat pumps, which are powered by 100 % renewable electricity. Heat accumulators in combination with heat pumps for a better coordination with renewable electricity generation make these assumptions plausible. As described in the previous section, synthetic methane is imported from North Africa. In North Africa, it is assumed that the synthetic methane is produced using electricity from renewable energy sources and that direct air capture (DAC) is used to gain CO$_2$. Further upstream emissions are not taken into account.

Fig. 2 shows the annual CO$_2$ emissions of the technologies in the building categories considered. From an environmental perspective, using heat networks with the current heat mix to supply existing MFH is the least attractive option, because this causes CO$_2$ emissions nearly twice as high as supplying heat with a gas condensing boiler. Heat pumps are the technology with the lowest CO$_2$ emissions despite the current power mix still including a large share of coal-fired electricity. This result is also found in the other building categories. The development in 2050 shows, that natural gas is the least attractive solution due to its CO_2 emissions.

Summary, conclusions, and outlook

To achieve ambitious climate protection targets, fossil energy sources have to be almost completely replaced by renewable ones by 2050. This requires new technical solutions for the supply of energy. The distribution networks for electricity, gas, and heat play a prominent role in the necessary transformation based on the current annual investments of 5 billion euro in Germany, and the strong influence they have on the final energy prices for gas, electricity, and heat. This gives rise to the question, which distribution networks will still be required in the future. Another question is how the different kinds of distribution networks can be integrated more closely with each other using new technologies, such as electric heat pumps in heat networks, an issue which now falls under the topic of sector coupling.

From a regulatory viewpoint, gas and electricity distribution networks, as well as heat networks, are planned independently of each other at present. The tax burdens on the three energy sources also differ strongly, with the electricity price bearing the biggest burden per kWh compared to gas and heat. Nevertheless, because of their high efficiency, heat pumps are the most favorable solution in almost all building categories considered today and in 2050 under the assumptions made, with the exception of currently existing buildings, if (partial) refurbishment is disregarded. In this case, gas condensing boilers are the most cost-effective solution. The comparison assumed constant shares of network charges until 2050. Taking into account the decreasing gas demand and the increasing electricity demand the gas network charges would increase, and the electricity network charges decrease, making heat pumps an even more economically attractive option. From an environmental viewpoint, however, heat pumps currently already have the lowest CO_2 emissions. In 2050 – assuming a decarbonized electricity sector – both heat pumps and a connection to the district heating network are the ecologically most attractive options.

Economically and environmentally, the most attractive option for residential end-users seems to be an electricity-based heat production in buildings, leading to the question of whether a parallel development of three different infrastructures is the best path for achieving GHG reduction targets or whether it would not be better to focus on the development of one or maybe two infrastructures. This raises the question, how much money should be invested in the natural gas distribution networks for supplying heat to buildings. Managing the transition phase in which the demand for gas falls sharply and, as a result, the specific gas network costs rise substantially, will be especially challenging for those households still dependent on gas supplies, gas suppliers and politicians. The design of this transformation process should be examined in greater depth in the future.

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