Future Economic Efficiency of Gas Distribution Grids

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***Abstract*—One crucial aspect to evaluate different options for sector coupling technologies is the future development of the energy infrastructure with its long operating lifetime and renovation cycles. On the one hand, gas demand in Germany is slightly decreasing during the last years and with necessary renovation rates, efficiency measures, as well as an upcoming electrification, a further decrease is certain. On the other hand, the use of Combined heat and power (CHP) is spreading particularly to provide heat to larger building complexes and power-to-gas is foreseen to be needed for seasonal storage of renewable energies. In this paper, these future aspects and their impact on the economic efficiency of gas distribution grids in Germany are investigated. With the benchmark gas distribution network as a reference, the future development is analyzed in three scenarios: Efficiency, electrification and renewable gas only. It is shown, that under certain circumstances parts of the distribution grid should be shut down, to prevent grid charges from rising.**

I. Introduction

The energy system in Germany is experiencing crucial changes. With the so-called "'Energiewende"', following also the Paris agreement, efficiency measures have to be implemented, as well as a transformation to 100 % renewable energies on the long run [1]. This implies great challenges for the existing gas infrastructure, which carries foremost fossil natural gas. A decrease of the gas demand leads to rising grid charges. Yet, the relation of different measures is rather complex: oil heating may be replaced foremost with gas heaters, the use of combined heat and power (CHP) is spreading particularly in larger building complexes and power-to-gas is considered the only option to store renewable energies over large time periods [2]. On the contrary, an electrification with more efficient heat pumps will take place and it is out of question that houses will become more efficient and thus demand less energy. On top of this, it is still unclear if the lower levels of the distribution grid will experience an increasing gas demand due to the Power-to-gas technology, using renewable gas foremost in CHPs, or if the gas is mostly used in gas power plants. This paper introduces a simple model to calculate the economic efficiency of a gas grid and gives an overview about how the changes will affect the economic efficiency of the gas distribution grid.

II. State of the Art

Already 2011 in the UK, the MARKAL Model Review "'Pathways to 2050"' suggested working towards abandoning low-pressure gas networks by 2050 [4]. In Germany are already numerous studies, that were carried out to show the importance of the gas grid for seasonal storage and to integrate renewable energies, e.g. [3]. They mostly focus on the upper grid levels, which seems to dominate the discussion in Germany.

III. Assumptions

The economic efficiency is calculated based on a benchmark grid and thus is valid only for inner-city distribution grids. For monopolistic grids, speaking of an economic efficiency is difficult, as the users of the grid will always pay for it. This may change, when certain points are reached. In this paper, the price for thermal energy by heat pumps (hp) is used as a reference to the gas-price. It is assumed, that if gas prices rise above that mark, users will more likely switch to hps and the low pressure grid might risk to be abandoned.
For the calculations, a classification of the assumptions is performed, to be able to transfer these to other grids. They include the grid itself, its consumer structure, the CAPEX and OPEX of the infrastructure as well as the WACC of the distribution system operator (DSO). The grid infrastructure is a natural monopole. To prevent infrastructure costs from rising, DSOs are regulated, which in Germany is governed by the Incentive Regulation Ordinance (ARegV - Anreizregulierungsverordnung) [5]. Every DSO is going through a benchmarked comparison process to calculate its efficiency for a period of five years, which is used to set its revenue ceiling. The inefficiency has to be eliminated over this period. This is realized by cutting 20 % of the inefficient costs every year from the revenue ceiling. Thus, in the 3rd year, the average revenue ceiling is exceeded. Only this revenue ceiling can be claimed to set the grid charges for the customers to finance the grid [6].

A. Benchmark grid

The benchmark gas distribution grid referred to in this paper is described in [7]. It consists of a high-pressure distribution

TABLE I
CHARACTERISTICS OF THE BENCHMARK GRID

Parameter	unit	value
total pipe length	m	16510
total pipe length high pressure	m	3500
total pipe length medium pressure	m	7160
total pipe length low pressure	m	5850
number of pressure regulators	#	4

TABLE II
CONSUMER STRUCTURE

Consumer	connection rate	consumption [kWh/year]
526 households (mult. dwellings)	0.7	4 799 487
339 detached dwellings	0.7	8 277 024
164 semi-detached dwellings	0.7	2 878 036
school	1	749 980
hospital	1	3 420 000
sum		**20 124 547**

circle (12 bar), feeding a low-(0.05 bar) and two medium-pressure (0.7 bar) areas. Characteristic parameters of the network are shown in table I.

B. Consumer structure

As the grid is an inner-city grid, consumers are mostly households in (semi-)detached or multiple dwellings. Table II gives an overview, how the consumers in the grid are structured. Assumptions for the gas demand of households were chosen based on [8]. Gas demand for the school and hospital are based on [9].

These assumptions lead to an average yearly consumption per meter of pipe of 1218.9 kWh/m/a, without inclusion of the superior grid levels. It is nevertheless already higher than the average in Germany, which is around 1644 kWh/m/a over all grid levels [10]. The deviation can be blamed on the neglect of industry, which is connected mainly to the upper grid levels.

C. Assumptions for costs in the grid

The main costs in a grid are the investment costs, of which pipes have the highest share. Figure 1 shows the assumptions made for the costs of piping, based on [11]. There is a big difference in costs of inner-city piping compared to rural piping, as underground construction costs significantly rise due to a higher share of complex road constructions in densely populated areas.

The OPEX (operational expenditures) in the grid were assumed by a factor of 5 €per pipe-meter and year [12].

D. Development of gas and electricity prices

Cheap gas prices are one of the arguments, why house-owners keep gas heating instead of exchanging it with a hp. This could change, if gas prices would significantly rise above the prices for thermal energy produced by a heat pump. The forecasts of two studies are used, to define a break-even-point,

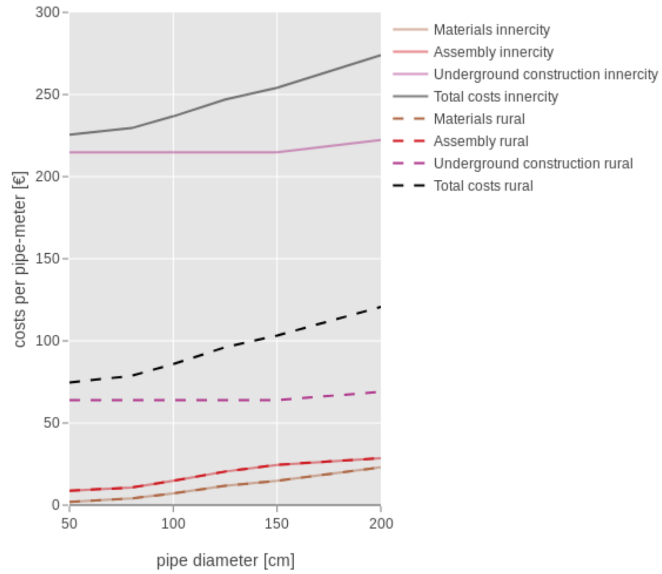

Fig. 1. Piping costs depending on the diameter based on [11]

when heat pumps become cheaper than gas, without the rising grid charges.
Figure 2 visualizes the forecasts for prices of gas (orange), biogas (violet) [13] and the import of synthetical renewable gas (red, transparent, dashed) [14]. In dotted black, the assumptions for electricity prices(heat pump tariff) from the same study were multiplied with annual coefficient of power (COP) values of air source heat pumps (ashp). It is assumed to be 2.6 in 2011 and to rise by 0.1 every ten years to reach an annual COP of 3 by 2050, which is rather conservative.
The figure shows, that the heat pump in average becomes less expensive by already 2024. Nevertheless, there is a great spread in the assumptions and the range of the gas price still remains close to the average price for the heat pump. It also shows, that the import price of synthetical gas could come close to the price of heat pump energy in 2050.

IV. METHODOLOGY

Rating the economic efficiency is more than just calculating the profit, since its behaviour is complex due to the mechanisms of the natural monopole and the related market regulation. A simple model has been developed in this work, to calculate the resulting grid charge and to put the resulting gas price into a context to rival technologies. Figure 3 illustrates the calculation of the grid charge, which is explained in the further sub-chapters.

A. Calculation of CAPEX and OPEX

The CAPEX (capital expenditures) consist of the investment costs. They are converted to annual costs by multiplication

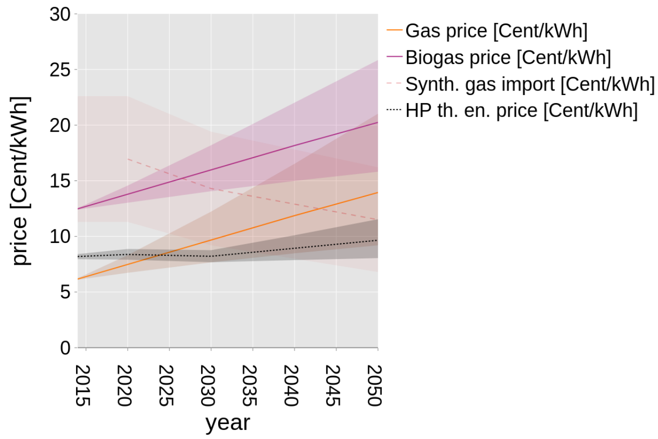

Fig. 2. Gas prices vs. thermal energy price from ashp

with the annuity factor. Together with the annual operational costs for the network OPEX, they form the total expenditures (totex, equation 1 [15]). It has to be noted, that consumption costs as well as other costs (such as insurance), as proposed by [16], were neglected.

$$totex = CAPEX \cdot a + OPEX \tag{1}$$

The annuity a is calculated based on equation 2.

$$a = \frac{(1 + WACC)^n \cdot WACC}{(1 + WACC)^n - 1} \tag{2}$$

with WACC being the weighted average costs of capital, which was implied as overall capital interest rate. The WACC is described by equation 3 [17].

$$WACC = r_{dc} \cdot \frac{DC}{TC} \cdot (1 - t) + r_{ec} \cdot \frac{EC}{TC} \tag{3}$$

where r_{dc} and r_{ec} are the interest rates for debt (DC) and equity capital (EC), TC is the total capital and t is the implicit tax rate. r_{ec} is defined by equation 4 [17]:

$$r_{ec} = r_{rf} + \beta \cdot (r_m - 1) \tag{4}$$

with β representing the risk factor [17], and r_{rf} and r_m the interest rates for risk-free capital (rf) and the market capital (m), which were chosen based on [18] and [19]. Table III gives an overview over the chosen assumptions.

B. Calculation of the revenue ceiling

As already pointed out, gas grid operators are regulated due to the natural monopole of gas grids. To simulate a market, each DSO is compared to a benchmark to define its efficiency. The resulting inefficient costs have to be eliminated (by 60 %) over a period of five years. This is ensured by fixing the revenue ceiling for each DSO, which for the second regulation period is defined by equation 5 [5]. This way, a continuous increase in efficiency is granted. The grid charges financing the network are based upon this revenue ceiling [6].

TABLE III
ASSUMPTIONS

Parameter	Assumption
debt capital interest rate [%]	3.7
risk-free interest rate [%]	0.5
implicit tax rate [%]	20.5
risk factor beta	0.95
equity share [%]	15
market interest rate [%]	5.7
lifespan n [a]	55

TABLE IV
REVENUE CEILING: ASSUMPTIONS

Parameter	Assumption
$C_{ni,t}$	90 000 €
Efficiency E	90 %
D_t	0.6
CPI_t	106.9 %
CPI_0	100 %
PF_t	1.5 %
year 0	2010

$$\begin{aligned} RC =& C_{ni,t} + (C_{tni,0} + (1 - D_t) \cdot Ci, 0) \cdot (\frac{CPI_t}{CPI_0} - PF_t) \\ & \cdot EF_t + Q_t + (VC_t - VC_0) \end{aligned} \tag{5}$$

where $C_{ni,t}$ are non-influencable costs in the considered year t, which in this paper are assumed to be only the costs for the superordinate network; $C_{tni,0}$ (temporarily non-influencable costs in the basis year 0) and $Ci, 0$ (influencable costs in the basis year 0) are calculated by multiplying the $totex$ with the efficiency E and inefficiency $(1 - E)$ (see equation 6 and 7 [6]); D_t is the distribution factor for each considered year t (ranging from 0.2 in the first year to 1 in the last); CPI is the consumer price index [20] and PF_t is a sectoral productivity factor [6]. Due to the complexity, all other factors are neglected in this work.
The costs for the superordinate network are assumed to account for one fourth of the annual costs of the distribution grid.

$$C_{i,0} = totex \cdot (1 - E) \tag{6}$$

$$C_{tni,0} = totex \cdot E \tag{7}$$

For this paper the year t is set to 2015 inside the second regulation period, ranging from 2013 to 2017. For this year, the parameters according to table IV were chosen.

C. Calculation of grid charges

Grid charges are calculated for each user category separately according to a cost-by-cause principle. In reality this leads to an approximately logarithmic curve of the grid charges,

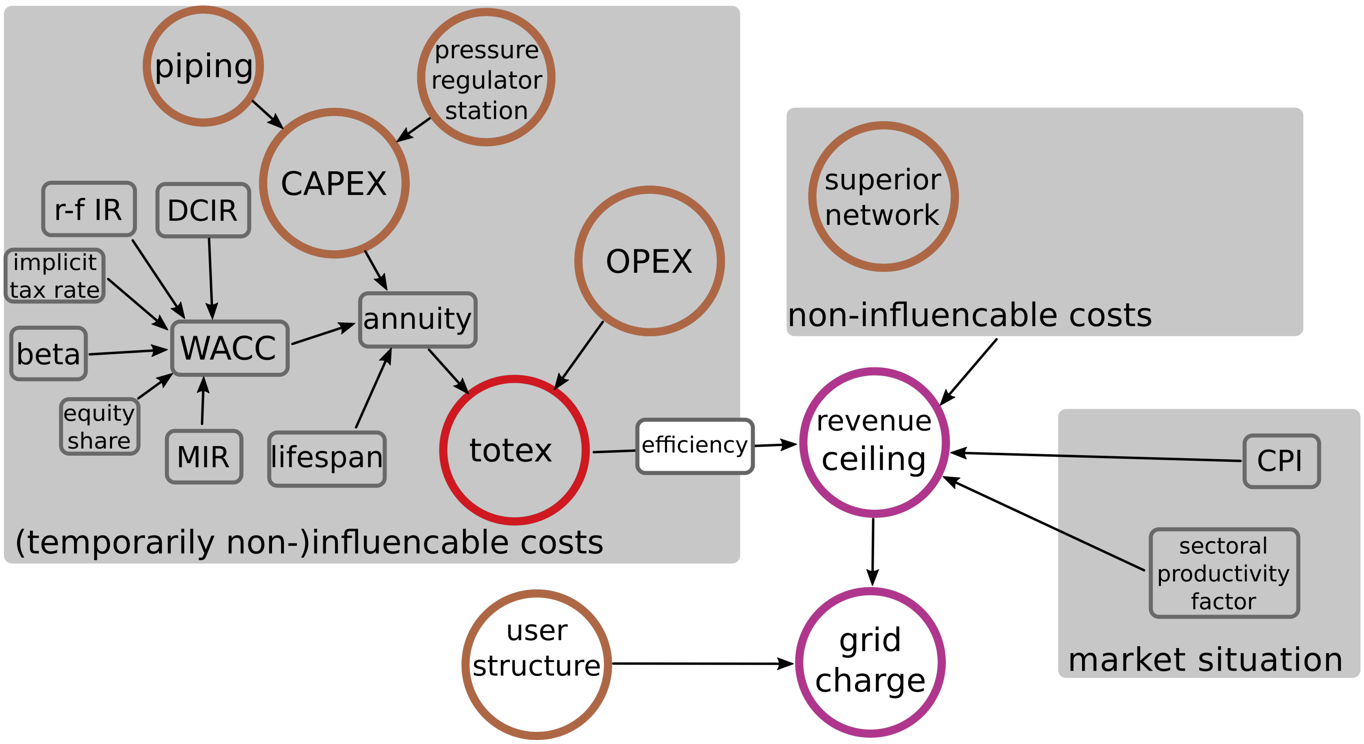

Fig. 3. Grid charge calculation

which converges to a minimum for the users with the highest yearly consumption, such as industry customers. Additionally the charges are separated into a power (basic, per year) and energy charge (per kWh). In this paper however, this complex calculation is neglected and only an average grid charge (gc) per kWh is calculated according to equation 8.

$$gc = \frac{RC[€]}{consumption[kWh]} \tag{8}$$

V. Results, sensitivities and discussion

An average grid charge of 1.85 Cent/kWh is calculated with the given methodology and assumptions. This is higher than the average grid charge in Germany, which in 2017 was 1.52 Cent/kWh [21] and can be explained only partly in the same way as explained in chapter III-B. It is possible that the assumption of the overall consumption is underrated due to the partly neglect of industry and business.
Another explanation is the big influence of certain assumptions onto the results. To give an overview about the sensitivities of the results according to the different parameters, a simple linear variation of certain parameters has been performed and visualized in figure 4.

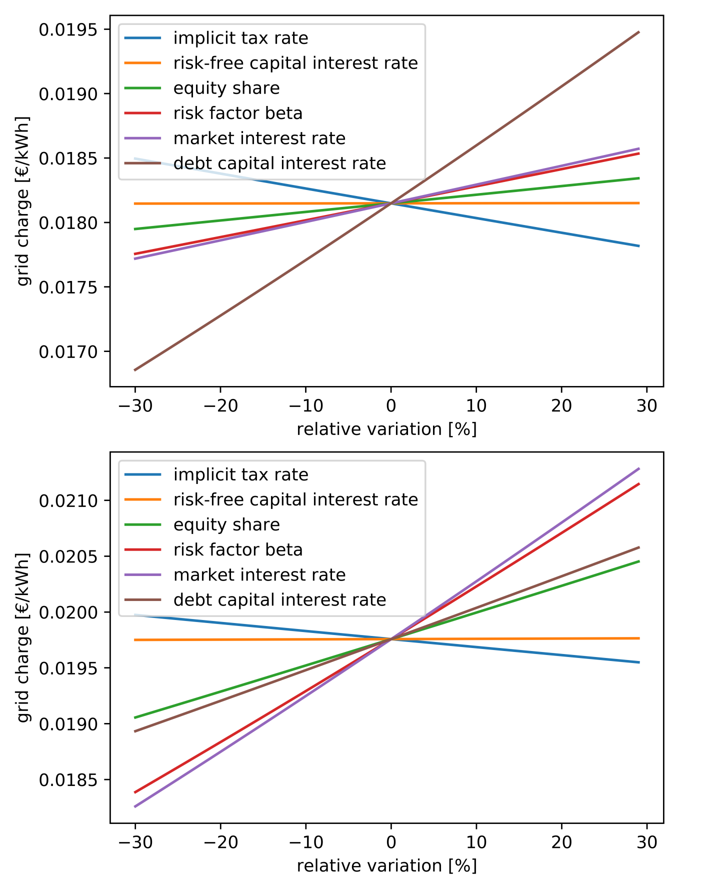

Fig. 4. Linear variation of assumptions based on the described (above) and with 50 % equity share (down)

The debt capital interest rate has the highest influence in this example. If the equity share rises, the market interest rate and the risk factor beta become more important. This means, that if the business case of a DSO is classified as more risky, this leads to higher grid charges.

VI. Scenarios

The main future developments of the gas infrastructure have already been named. They have been clustered into three scenarios, which are cross-linked to each other. The political aim is to reduce the thermal (non-renewable) primary energy demand for buildings by 80 % until 2050. Several studies investigated, under which circumstances this aim can be realized. Together with studies, that map the trend in the future development, they have been compiled in several meta-analysis by the Agency for Renewable Energy (AEE), which build the basis for this work [22].
Three different topics, concerning the future gas demand, have been identified and isolated in three scenarios. Scenario I addresses efficiency measures in thermal energy demand of buildings. It also includes the replacement of oil-vessels and the resulting potential for an increased gas demand. Scenario II builds up on the first and adds the electrification, namely the replacement of gas heating by heat pumps. Both scenarios show a development range, which is due to the variety of studies. The resulting gas demand is used to calculate the consequential grid charges. Together with predicted gas prices they form the future gas prices in total. Scenario III addresses the question, whether it is possible to provide the future gas demand by renewable gas only.

A. Scenario I: Efficiency

To meet the primary energy reduction targets for buildings, studies evaluated by the AEE came to the conclusion, that a maximum of 54 % of reduction is needed. It is nevertheless unclear how this reduction is achieved and thus, other studies see the trend for 2050 in the overall reduction going to just 18 % [22]. These two reduction points were transferred to the minimum and maximum of gas demand in 2050. In addition, the energy consumption of oil-vessels (from 2016) [23] was added to the maximum, which leads to a slightly higher gas demand than today. The resulting path is shown in figure 5.

The resulting gas demand range was linearly converted to the benchmark grid to calculate the range of the grid charge, which yields to charges of 1.56 Cent/kWh up to 4.03 Cent/kWh in 2050. Additional investments to connect the supplementary households to the gas grid were neglected. They would lead to a significant rise of the grid charge, as numerous detailed measures of grid extension would be necessary.

B. Scenario II: Electrification

As mentioned, the most promising concurrence to gas heating are heat pumps. Studies evaluating their potential contribution to the heating demand come to results between 14.56 and 244.56 TWh for Germany in 2050 [22]. It is assumed, that

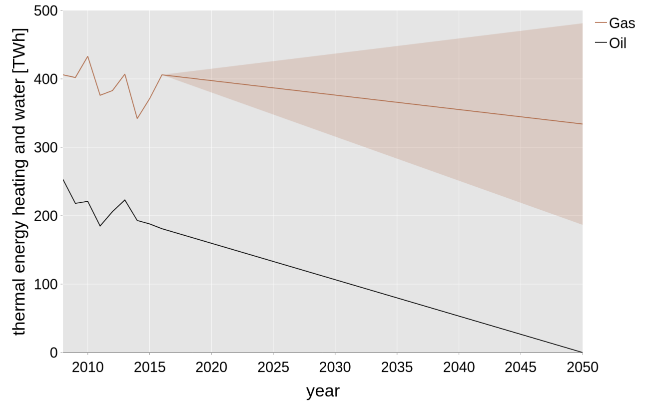

Fig. 5. Scenario I: Development of gas demand for heating based on [22] and [23]

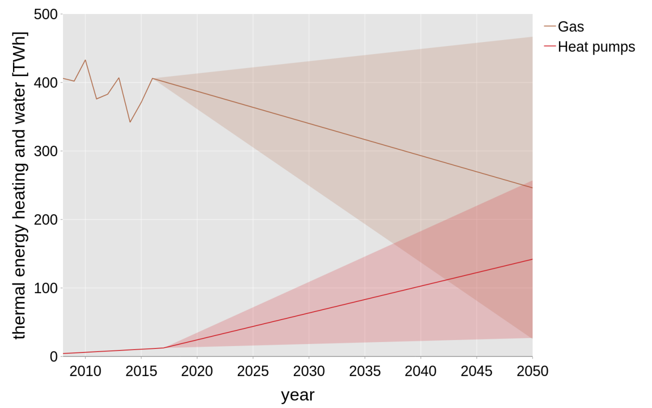

Fig. 6. Scenario II: Development of gas demand for heating based on [22] and [23]

the gas demand plus the demand for oil calculated in scenario I is substituted by the range of energy demand covered by heat pumps, as shown in figure 6. This leads to an overall grid charge between 1.61 Cent/kWh and 29.58 Cent/kWh. The electrification and thus the use of heat pumps is politically wanted. It can be assumed, that a higher dissemination of heat pumps is likely and that the average scenario might occur. This would lead to grid charges of around 16.04 Cent/kWh in the given case, which would be higher than the foreseen average price of gas itself at that time.
To react to these circumstances, it would be almost inevitable to shut down parts of the gas distribution grid.

C. Scenario III: Renewable gas

Using renewable gas only from a DSO's point of view leads to the question, how this gas is fed into the grid. The feed-in of biogas is not yet common. Instead it is mostly used directly in CHP plants to produce heat and electricity. This is understandable, looking back at the high price for biogas, which is also due to the rather complex preparation of biogas to biomethane needed to feed it into the grid. In addition, the connection of biogas plants to the grid is costly also for the DSO, which in some cases has to pay for the piping to

the contact point. These investment costs can nevertheless be considered as marginal in comparison to the rest of the grid.
It is out of question, if it would be theoretically possible to supply the gas demand of the two scenarios by renewable gas, as it could also be imported. The question is rather: would it be profitable? The biggest challenge for a 100 % renewable energy system is the time in winter, with clouds and without wind, which regularly occur. In this time, a huge amount of installed capacity is needed, to provide the necessary electricity. This leads to the assumption for a lot of studies, that gas power plants will grow in importance in the future. In contrast to this, it could also mean, to bridge this period with decentralized CHPs, providing heat for households or villages and electricity at the same time. They would also self-regulate the electrical grid, as they produce electrical energy at the same time as heat pumps need it.
If this scenario would turn out to save costs for the electrical infrastructure, this could save parts of the gas distribution grid. It is nevertheless questionable, if it would be necessary to keep the whole grid. In the range of this paper it was not possible to give a clear answer to this potential. It will be adressed in future works.

VII. Conclusion

Rating the economic efficiency of gas distribution grids can only be performed in the context of the power sector, as the costs of grid operation is borne by the consumers. As a concurrence for the heating with gas, heat pumps were introduced with their operational costs as a reference factor. A simple model has been developed to calculate grid charges. On the basis of a benchmark gas distribution grid, it was shown, that the mixture of efficiency measures and electrification will lead to such a significant decrease in gas consumption, that parts of the grid have to be shut down, to prevent grid charges from rising too high. Renewable gas in CHP plants is seen as a potential chance to increase the gas consumption and at the same time stabilise the electrical grid. This option will be investigated in future works.

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