

Network Design Optimization for Biomethane Feed-in from Decentralized Production Sites

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ABSTRACT

Biomethane can serve as an alternative to fossil fuels. Pipeline and compressor infrastructure must be built to enable the feed-in of biomethane from decentralized production sites into the existing gas network. Costs can be reduced by sharing this transport infrastructure among individual biogas plant operators. To find the cost-optimal layout, a mixed integer linear programming (MILP) problem is formulated. The model is expanded to show the effect of considering not only pipe cost but also compressor cost in the objective. It is applied to an Austrian region to find the optimal network for 14 biogas plants. After optimization, two allocation methods for sharing investment costs among biogas plants are explored: an equal cost approach and a volumetric share approach. Optimal network topology changes due to the modified objective, resulting in significant cost savings of 9 % for the total region and 19 % for a subregion. Investment costs for individual biogas plant operators vary widely, depending on network configuration and chosen allocation method.

Keywords: Energy Systems, Biofuels, Optimization, MILP

INTRODUCTION

To mitigate climate change, anthropogenic greenhouse gas emissions must be drastically reduced. A great share of these emissions is caused by fossil fuels used in industries. While many sectors can be decarbonized through electrification, eliminating fuels is difficult in others. For example, many industrial processes require high temperature heat [1].

Biofuels can serve as an alternative to fossil fuels, particularly biomethane. Biomethane is produced by processing biogas that results from the fermentation of biogenic residues [2, 3].

In Austria, 74.37 TWh of gas were consumed in 2024. Around 124.52 GWh or 0.16 % of this consumption was covered through biomethane [4]. A law proposal to increase the quota of renewable gases failed in 2024 [5]. However, the current Austrian government has announced a new attempt to pass such a law in its government programme for 2025-2029. The target of 6.5 TWh of renewable gases per year should be reached by 2030 [6]. Currently, most of the biogas produced in Austria is used for on-site electricity and heat generation in combined heat and power (CHP) plants instead of being

upgraded to biomethane. In 2024, almost 300 plants generated electricity from biogas [7]. These plants are located decentrally and are usually small. More than two-thirds of the mentioned biogas CHP plants have a maximum capacity lower than 500 kW_{el}, with the average maximum capacity of these being 164 kW_{el} [8]. In comparison, only 14 plants delivered biomethane to the gas grid [9]. To increase the quota of biomethane, investment in upgrading and transport infrastructure is necessary. Individual biogas plant operators can benefit from economies of scale when cooperating with each other along the biomethane supply chain [10].

A primary decision is how to find a cost-effective pipeline network topology to connect biogas plants and enable feed-in. Hengeveld et al. [11] found that biogas transport costs can be reduced when connecting plants using a fishbone layout. Recent publications presented mixed integer linear programming (MILP) models to determine network topology via mathematical optimization. These models are based on mathematical formulations for finding minimal spanning trees. Schröer et al. [12] provided a model to cluster decentralized biogas plants and connect them to central upgrading facilities and feed-in points while maximising profit. Again, this publication

found great potential for cost savings due to shared infrastructure compared to individual solutions. A recent publication of Blanco et al. [13] presented a MILP model for designing waste-to-biomethane logistics, covering large parts of the biomethane supply chain from waste collection to feed-in and biomethane liquefaction. However, none of these models include feed-in conditions in detail. When clustering projects are implemented in practice, feed-in capacities as well as minimal pressure levels of feed-in points must be met.

In this paper, a minimum spanning tree MILP formulation for biogas networks proposed by Huber et al. [14] was enhanced to include individual feed-in capacity limits and pressure requirements into the model. In this way, the cost of compression is considered in detail. The model is applied to a real use case in Austria. To demonstrate the effects of model extension, the optimization results of both the previous and enhanced models are compared.

MATERIAL AND METHODS

Use Case

The study examines clustering and connecting 14 biogas plants to the existing gas grid. 15 possible feed-in points are considered in the optimization. Locational data, production and capacity volumes, as well as pressure levels, correspond to existing plants and connection points in Austria. The 14 biogas plants are defined by their location and their biogas production volume, which lies between 83 and 402 Nm³/h. The 15 feed-in points are characterized by their location, maximum feed-in capacity, and the required pressure level for feed-in. Feed-in capacities range from 291 to 2910 Nm³/h. Pressure levels are defined by the operational pressure of the existing gas network and are 3.6, 8, 12.5, or 67 barg.

MILP Model

The MILP model is based on the network optimization formulation proposed by Huber et al. [14]. Constraints regarding feed-in point capacity limits and compressors were added.

The problem is formulated using incidence matrices introduced in Equation (1). The adjacency matrix C_{BP} indicates connections of biogas plants to each other. The matrix element $C_{BP,ii'}$ takes the value 1 if biogas plant i is directly connected to plant i' and biogas is transported from plant i to i' . The adjacency matrix C_{FP} indicates connections of biogas plants to feed-in points identified with index j . Equation (2) limits the self-connection of biogas plants.

d_{BP} and d_{FP} are matrices with spherical distances between locations of biogas plants or biogas plants and feed-in points. As the problem is highly combinatoric, Equations (3) and (4) improve computing time by

excluding connections longer than the median distance between biogas plants $\bar{d}_{BP}$ – respectively the median distance between biogas plants and feed-in points $\bar{d}_{FP}$ – from the feasible solution space.

$$C_{BP,ii'}, C_{FP,ij} \in \{0, 1\} : \forall i, i', j \quad (1)$$

$$C_{BP,ii} = 0 : \forall i \quad (2)$$

$$C_{BP,ii'} = 0 : \forall (i, i') \in \{(i, i') \mid d_{BP,ii'} > \bar{d}_{BP}\} \quad (3)$$

$$C_{FP,ij} = 0 : \forall (i, j) \in \{(i, j) \mid d_{FP,ij} > \bar{d}_{FP}\} \quad (4)$$

Binary edge matrix C_E describes how many edges are used to connect individual plants to feed-in points. For each plant i , the index e of the column containing a non-zero entry is the number of edges between the plant and the feed-in point. The construction of the edge matrix is given in Equation (6). The operator $\otimes$ is defined as a Boolean product of a matrix and a vector. Further description of this operation can be found in [14]. Equation (7) ensures that each biogas plant is connected to the grid.

$$C_{E,ie} \in \{0, 1\} : \forall i, e \quad (5)$$

$$C_{E,ie} = \begin{cases} \sum_j C_{FP,ij} & \text{for } e = 1 \\ C_{BP} \otimes C_{E,ie-1} & \text{for } e > 1 \end{cases} : \forall i \quad (6)$$

$$\sum_e C_{E,ie} = 1 : \forall i \quad (7)$$

Matrix $\dot{V}$ is a helper variable to calculate accumulated flows in the network from biogas plant production flows $\dot{V}_{BP,i}$. Equation (8) describes the construction of the helper variable. Vector $\dot{V}_{FP}$ contains accumulated flows at feed-in points and is calculated by Equation (9). Compliance with capacity limits of feed-in points is ensured by Equation (10).

$$\dot{V}_{ie} = \begin{cases} \dot{V}_{BP,i} & \text{for } e = 1 \\ \dot{V}_{BP}(C_{BP} \otimes C_{E,ie-1}) & \text{for } e > 1 \end{cases} : \forall i \quad (8)$$

$$\dot{V}_{FP,j} = \sum_i (C_{FP,ij} \sum_e \dot{V}_{ie}) : \forall j \quad (9)$$

$$\dot{V}_{FP,j} \leq \dot{V}_{\max,j} : \forall j \quad (10)$$

Vector p_{out} is a binary variable that defines the chosen pressure category for each feed-in point that is used. According to Equation (12), only one pressure category k can be chosen for each feed-in point j . Equation (13) constrains the chosen compressor outlet pressure to be greater than the necessary pressure at feed-in points $p_{FP,j}$. The upper limit of each pressure category is denoted in parameter vector $p_{out}^{\lim}$ and given in the next subsection.

$$p_{out,jk} \in \{0, 1\} : \forall j, k \quad (11)$$

$$\sum_k p_{out,jk} \leq 1 : \forall j \quad (12)$$

$$\sum_k p_{out,jk} p_{out,k}^{\lim} \geq p_{FP,j} : \forall j \quad (13)$$

Annual investment and operational costs for pipes C_{CAPEX}^{pipe} and C_{OPEX}^{pipe} were calculated after Equations (14) and (15) with an annualization factor AF_{inv} . Parameters c_{CAPEX}^{pipe} and c_{OPEX}^{pipe} are given in the next subsection.

$$C_{CAPEX}^{pipe} = AF_{inv} c_{CAPEX}^{pipe} \sum_i (\sum_{i'} C_{BP,ii'} d_{BP,ii'} + \sum_j C_{FP,ij} d_{FP,ij}) \quad (14)$$

$$C_{OPEX}^{pipe} = c_{OPEX}^{pipe} \sum_i (\sum_{i'} C_{BP,ii'} d_{BP,ii'} + \sum_j C_{FP,ij} d_{FP,ij}) \quad (15)$$

Compressor capital investment C_{CAPEX}^{comp} is described by the exponential expression in Equation (16). Constant c_{CAPEX}^{comp} and exponent k_{CAPEX}^{comp} are given in the following subsection. This nonlinear equation was approximated through piecewise-linearization and implemented with SOS2. Operational costs C_{OPEX}^{comp} of compressor units at feed-in points are calculated through Equation (17). The energy demand of pressure category k is $e_{comp,k}$. This and other parameters, namely the annual operating hours t_{op} , the electricity price c_{el} , and the share of investment cost for maintenance c_m are given in the next subsection.

$$C_{CAPEX,j}^{comp} = AF_{inv} c_{CAPEX}^{comp} \dot{V}_{FP,j}^{1-k_{CAPEX}^{comp}} : \forall j \quad (16)$$

$$C_{OPEX,j}^{comp} = \sum_k (e_{comp,k} p_{out,jk}) \dot{V}_{FP,j} t_{op} c_{el} + c_m C_{CAPEX,j}^{comp} : \forall j \quad (17)$$

The optimization model is run with two different objectives, both minimizing total annual cost. The first objective in Equation (O1) only considers the cost for pipes and is therefore used to calculate the benchmark case where the pressure levels of feed-in points are not considered during optimization. The second objective in Equation (O2) includes the costs of compressors, exploiting the full potential of the enhanced model. By comparing the results of both optimization runs, the effect of the model enhancement can be evaluated.

$$\min C_{CAPEX}^{pipe} + C_{OPEX}^{pipe} \quad (O1)$$

$$\min C_{CAPEX}^{pipe} + C_{OPEX}^{pipe} + \sum_j C_{CAPEX,j}^{comp} + \sum_j C_{OPEX,j}^{comp} \quad (O2)$$

Parametrization

CAPEX and OPEX of pipes and compressors are annualized. Useful life is assumed to be 20 years, so the annualization factor AF_{inv} is 0.05 1/a.

Pipe costs in Table 1 are selected according to expert recommendation from the industrial project partner ÖVGW [15]. The investment and operational costs of compressors were modelled based on an internal report from the project partner ÖVGW [16]. According to this study, capital expenditures for compressors can be described by the nonlinear relation in Equation (16). The

coefficient c_{CAPEX}^{comp} and exponent k_{CAPEX}^{comp} of the compressor CAPEX equation are dependent on compressor inlet pressure, which is assumed to be 0.1 barg for all compressors in the described use case. Therefore, coefficients are set to the values in Table 2.

Table 1: Pipe parameters [15].

Parameter	Value	Unit
c_{CAPEX}^{pipe}	275	EUR/m
c_{OPEX}^{pipe}	1	EUR/m/a

Table 2: Compressor parameters [16]. Electricity cost for non-households between 20 and 500 MWh/a in the first half of 2025 [17].

Parameter	Value	Unit
c_{CAPEX}^{comp}	83 688	EUR*h/Nm ³
k_{CAPEX}^{comp}	0.648	-
t_{op}	8500	h/a
c_{el}	0.28	EUR/kWh
c_m	4	%

Equation (17) describes operational expenditures of compressors, including energy cost and maintenance costs. Energy cost depends on the electricity price and the amount of energy necessary for compression. Table 3 contains compressor pressure categories and the respective energy demand for compression. Electricity price and maintenance cost can be found in Table 2.

Table 3: Compressor outlet pressure categories and respective energy demand [16].

p_{out}^{lim} in barg	e_{comp} in kWh/Nm ³
3.6	0.1094
8	0.1450
12.5	0.1807
28	0.2369
70	0.2888

Cost Allocation

When clustering biogas plants, it is essential to find a fair method of allocating investment and operating costs of the shared infrastructure. Different methods have been proposed, e.g., equal cost for all cluster participants, sharing costs depending on the volumetric flow rate of participants, or on the distance to a feed-in point [18].

In this paper, the equal cost (EC) and volumetric share (VS) allocation method is applied after optimization to split CAPEX for pipes and compressors among participants in the clusters. Equation (18) describes how CAPEX are allocated to individual biogas plants using the EC approach. $C_{CAPEX,i}^{EC}$ is the CAPEX allocated to biogas

plant i , while $C_{CAPEX,Cl}^{pipe}$ and $C_{CAPEX,Cl}^{comp}$ are total CAPEX of pipes and compressors of the cluster Cl that the respective plant is part of. $N_{BP,Cl}$ is the number of biogas plants belonging to the cluster. Analogously, Equation (19) presents CAPEX allocation using the VS method where $C_{CAPEX,i}^{VS}$ is the CAPEX allocated to biogas plant i and $\dot{V}_{FP,Cl}$ is the total flow at the feed-in point of the cluster.

$$C_{CAPEX,i}^{EC} = (C_{CAPEX,Cl}^{pipe} + C_{CAPEX,Cl}^{comp}) / N_{BP,Cl} \quad (18)$$

$$C_{CAPEX,i}^{VS} = (C_{CAPEX,Cl}^{pipe} + C_{CAPEX,Cl}^{comp}) * \dot{V}_{BP,i} / \dot{V}_{FP,Cl} \quad (19)$$

RESULTS AND DISCUSSION

The MILP formulation is applied to the previously introduced Austrian use case. The optimization problem is run twice, using the different objectives in Equations (O1) and (O2). Figure 1 depicts the resulting networks, and the corresponding system costs are shown in Figure 2.

When only pipe costs are minimized with the objective (O1), 7 clusters are formed as depicted in Figure 1a. In contrast, minimizing pipe and compressor costs with objective (O2) results in 5 clusters as shown in Figure 1b. A cluster of three biogas plants in the northwest, and two single biogas plants without connections to other plants in the middle and in the southeast remain unchanged by the modified objective. The boxes in Figure 1a and Figure 1b are used to enlarge areas where the cluster configuration changes due to the change of the objective function: In the northern area (Region 1), two clusters are combined into one. The feed-in point of the eastern cluster continues to be used. In the southern area (Region 2), two clusters are united into one. It is especially notable that none of the feed-in points used when minimizing objective (O1) in the east are used. Instead, biogas plants are connected to a previously unused feed-in point in the west.

Figure 2 discloses the result of the modified objective on system cost. For the total area, specific system costs from optimization with objective (O1) are 14.53 EUR/MWh of biomethane. With objective (O2), they reduce to 13.28 EUR/MWh, which is a reduction by 9 %.

When comparing costs obtained by using objective (O1) to those resulting from using (O2) on component level, costs for pipes increase by 0.48 EUR/MWh. At the same time, the decrease is 1.37 EUR/MWh in compressor OPEX and 0.36 EUR/MWh in compressor CAPEX. As cost reduction is caused by changes to the network in the two enlarged areas, costs for these areas are analysed separately in the lower four bars of the plot. The changed configuration in the north reduces total system cost from 13.74 to 12.94 EUR/MWh or 6 %. There, pipe costs increase minimally, but investment costs for compressors decrease by 0.48 EUR/MWh. In the southern area, total

system costs can decrease from 14.55 to 11.87 EUR/MWh or 19 % due to the modified layout. While pipe costs grow by 1.29 EUR/MWh, investment and operating costs of compressors can be reduced by 0.52 EUR/MWh and 3.45 EUR/MWh, respectively.

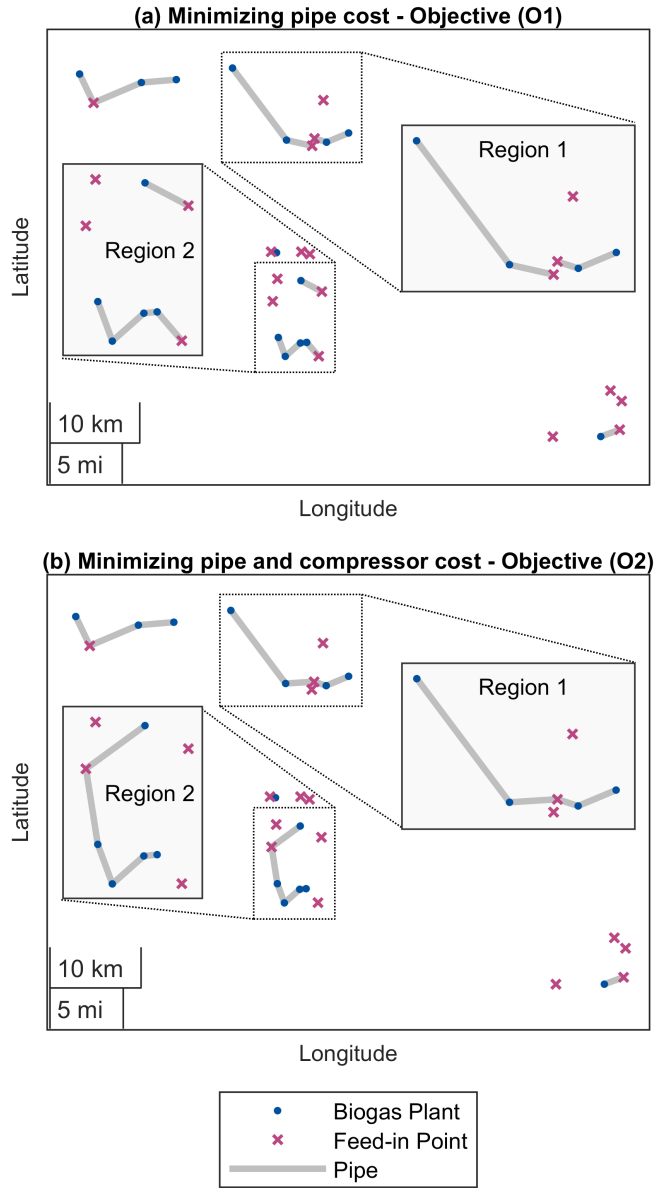


Figure 1. Network topology obtained by (a) optimization of pipe cost using objective (O1) and (b) optimization of pipe and compressor cost using objective (O2). Regions where clusters change due to the modified objective are magnified.

For Region 1, the modification of the objective leads to a change in network configuration. This is because compressor CAPEX can be reduced when only one compressor is built. However, operating cost changes only slightly, as the compressed amount of biomethane and, therefore, energy demand does not decrease. For Region

2, the cost structure changes more noticeably. Again, compressor CAPEX can be reduced by installing only one instead of two compressors. However, optimal feed-in locations change due to the modified objective. The reason for this is that eastern feed-in points operate at much higher pressure levels than the chosen feed-in point in the west. The great reduction of operating costs leads to a changed network combination with a slightly longer pipeline network.

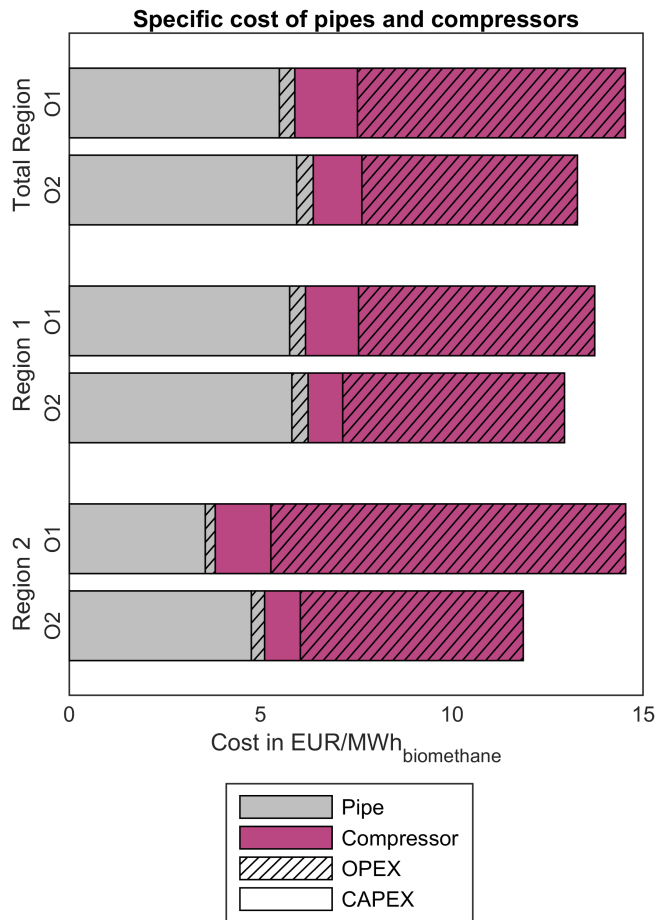


Figure 2. Specific cost of pipe and compressor infrastructure per MWh biomethane for the total region and magnified regions from Figure 1. The upper bar of each pair shows the cost of the network when minimizing only the pipe cost using the objective (O1). The lower bar shows the cost of the network when minimizing pipe and compressor cost using the objective (O2).

Figure 3 shows the results of applying the different allocation methods given in Equations (18) and (19) to the CAPEX of clusters in Region 1. Figure 3a and Figure 3b depict clusters from optimization with objectives (O1) and (O2). Biogas plants are numbered for identification. In Figure 3c, the allocated CAPEX cost per MWh of biomethane is plotted for each biogas plant in the region in a radar chart. Orange lines represent allocated cost after optimization with objective (O1), corresponding to

clusters in Figure 3a, where the same color is used for depicted pipes. Blue lines show allocated cost after optimization with objective (O2), corresponding to the cluster in Figure 3b that is plotted in blue as well. Dashed lines indicate values obtained by equal cost allocation, and solid lines represent values calculated by volumetric share allocation.

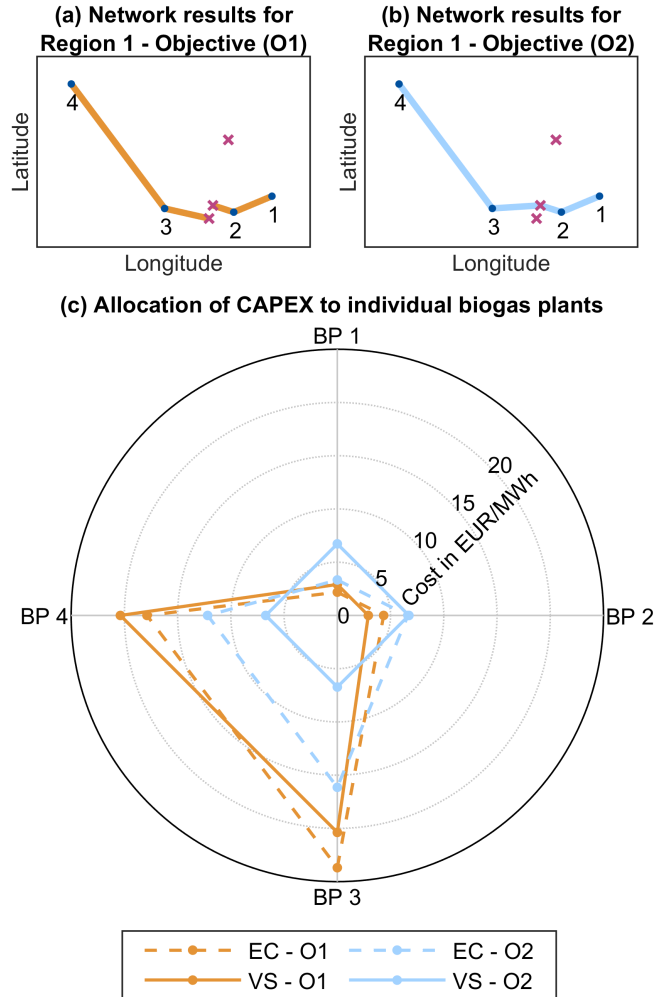


Figure 3. Network topology for Region 1 resulting from (a) optimization with objective (O1) and (b) optimization with objective (O2). Biogas plants (BP) are numbered for identification. Pipe colors are chosen corresponding to CAPEX allocation results in (c), where the equal cost (EC) and volumetric share (VS) methods are applied to both optimization results for all four biogas plants in the region.

Optimization with objective (O1) results in two clusters. CAPEX for the cluster containing biogas plants 1 and 2 are low, independent of the allocation method. This is caused by short pipeline distances and high biogas production volume in this cluster. Biogas plant 2 profits from VS allocation because its production flow is lower than the production flow of biogas plant 1. CAPEX for the

cluster containing biogas plants 3 and 4 are high, because pipe distances are long and the total biogas production volume of this cluster is low. Again, plant 3 profits from VS allocation because it has a lower production volume than plant 4. Optimization with objective (O2) results in only one cluster, so the total CAPEX now have to be allocated among all four biogas plants. Biogas plants 3 and 4 now reach much lower CAPEX costs than in the previous case, while the situation worsens for plants 1 and 2. This can again be reasoned with the lower production volumes of biogas plants 3 and 4 that additionally have much longer necessary pipe connections to the feed-in point. Independent of the allocation method, plants 3 and 4 profit from combining two clusters into one.

CONCLUSION AND OUTLOOK

In this paper, a mixed-integer linear programming-based network optimization problem for biomethane feed-in is extended to include modelling of compressor infrastructure. After optimization, two cost allocation methods are applied to the resulting networks to share the investment cost among participating biogas plants.

By including compressors in the optimization model, network layouts change, and system cost is reduced significantly. For the total region under investigation, a 9 % cost reduction is achieved; for one of the subregions, savings of 19 % are accomplished. The results undermine the importance of carefully selecting which components to model in energy system design optimization.

As a next step, additional system components, such as processing plants, should be included in the model. This is especially important because different upgrading technologies operate at different output pressures. Hence, further cost reductions can be expected when selecting the best technological fit for each feed-in point.

Moreover, this publication shows that investment cost for individual biogas plants can vary significantly based on the resulting network configuration and the chosen cost allocation method. It highlights that lowering total system cost and thereby achieving a better overall result does not always correspond to improving the situation for every participant when using established allocation methods. With equal cost and volumetric share allocation, some biogas plant operators can expect higher profits if they exclude other plants from the cluster.

To significantly increase the amount of biomethane fed into the grid and exploit the full potential in Austria, many biogas plant operators must participate. Two factors are detrimental to this development: Firstly, smaller biogas plants that are far from the grid face high investment costs. Secondly, large biogas plants close to the grid can take the opportunity and increase profits by excluding disadvantaged biogas plants from the network.

To aid the design of effective governmental incentives and regulatory frameworks, further research should investigate cost allocation and cooperation among biogas plant operators.

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NOMENCLATURE

Acronyms

BP	biogas plant
CHP	combined heat and power
EC	equal cost
FP	feed-in point
MILP	mixed integer linear programming
SOS2	special ordered sets of type 2
VS	volumetric share

Indices/Sets

$i \in \{1, \dots, N_{BP}\}$	biogas plant
$i' \in \{1, \dots, N_{BP}\}$	biogas plant
$j \in \{1, \dots, N_{FP}\}$	feed-in point
$e \in \{1, \dots, N_E\}$	edges
$k \in \{1, \dots, N_C\}$	pressure category

Optimization Variables

C_{BP}	binary matrix for connections between BPs
C_E	binary matrix indicating the number of edges to the FP
C_{FP}	binary matrix for connections between BPs and FPs
C_{CAPEX}^{comp}	vector of compressor CAPEX at FPs
C_{OPEX}^{comp}	vector of compressor OPEX at FPs
C_{CAPEX}^{pipe}	total pipe CAPEX
C_{OPEX}^{pipe}	total pipe OPEX
p_{FP}	vector of pressure at FPs
p_{out}	binary matrix of pressure category at FPs
$\dot{V}$	matrix of flows at edges
$\dot{V}_{FP}$	vector of flows at FPs
$\dot{V}_{max}$	vector of maximal capacities of FPs

Parameters

AF_{inv}	annualization factor
c_{CAPEX}^{pipe}	pipe investment cost parameter
c_{OPEX}^{pipe}	pipe operating cost parameter
c_{CAPEX}^{comp}	compressor investment cost parameter
c_{el}	electricity price
c_m	maintenance cost parameter
d_{BP}	matrix of distances between BPs
$\bar{d}_{BP}$	median distance between BPs
d_{FP}	matrix of distances between BPs
$\bar{d}_{FP}$	median distance between BPs and FPs
e_{comp}	compressor energy parameter
k_{CAPEX}^{comp}	compressor investment cost parameter
N_{BP}	number of BPs
N_{FP}	number of FPs
N_E	maximum number of edges between BP and FP
N_C	number of compressor pressure categories
p_{out}^{lim}	compressor outlet category parameter
t_{op}	operating hours
$\dot{V}_{BP}$	vector of BP production flows

Cost Allocation

$C_{CAPEX,i}^{EC}$	cost allocated to BP i through EC method
$C_{CAPEX,i}^{VS}$	cost allocated to BP i through VS method
$C_{CAPEX,Cl}^{pipe}$	pipe cost of total cluster
$C_{CAPEX,Cl}^{comp}$	compressor cost of total cluster
$N_{BP,Cl}$	number of BPs in cluster
$\dot{V}_{FP,Cl}$	flow at FP of cluster

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