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Line-pack storage in biogas infrastructures at regional scale, a model approach

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Summary

Previously, we reported on a biogas transport model; the model assesses transport costs in a grid with fishbone and star layout collecting biogas. Biogas collection from several digesters to a hub supports the efficient use of resources. A dedicated grid, used for transport, can serve as a form of biogas storage as well. So a model was developed to evaluate line-pack storage in a transport grid for different digester scale, number of digesters, region size, and grid type. Line-pack storage does not require additional investments, and variable costs consist of extra compression costs. In both fishbone lay-out and star lay-out estimated line-pack storage, costs are between 0.3 and 1.5 €ct m³h⁻¹. In a star lay-out, line-pack storage volume increases with region size. In a fishbone lay-out, the maximum line-pack storage volume is small in both a small size region and in a large region, as a result of pipeline volume and pressure restriction. A comparison of storage costs shows that line-pack storage can compete on costs with pressureless storage, but pressurized pipes are preferred for seasonal storage. A method to describe enlargement of line-pack storage by increased investment in pipelines depending on maximum transport pressure is presented. Such enlargement by applying larger pipe diameters could be financially sensible.

KEYWORDS

biogas grid, biogas pipeline, biogas storage costs, fishbone lay-out, line-pack storage, star lay-out

1 | INTRODUCTION

Biogas collection from several digesters to a hub could support the efficient use of renewable energy from biomass. Such biogas infrastructures are studied, planned, and developed, mainly in Europe.^{1–6} Generally, utilizing a hub to collect a larger volume of biogas induces a scale

advantage for the end user through cost reduction, eg, an upgrading facility.⁷ With electricity production by a biogas combined heat and power generator (CHP), a large improvement in overall energy efficiency can be achieved when heat generation can be matched with an appropriate heat demand; this is accomplished when biogas is transported to a place with such a demand.⁸

Nomenclature: capacity, the volume of (bio)gas passing a pipeline segment, pipeline, or grid, measured in m³h⁻¹; CHP, combined heat and power generator; configuration, dimensions of the pipelines and other components in a biogas grid; end user, the user of biogas that is transported by a biogas grid; this can be an upgrading installation, a CHP or boiler.; green gas, biogas upgraded to natural gas quality, also known as biomethane; hub, a central place to collect biogas for further processing; NPV, net present value; region, biomass source region, assumed to be a square with maximum side of 100 km; scale of a digester, the biogas production of a digester in m³h⁻¹; total grid capacity, total biogas production in a region, that is transported to a hub; volume of (bio)gas, volume of a gas is measured in m³ at standard conditions (temperature 273.15 K, absolute pressure 0.101325 MPa)

A biogas transport model was proposed by Hengeveld et al. Costs and energy use of biogas transport are presented for two grid types.⁷ In a star lay-out, digesters are individually connected by a pipeline to the hub. In a fishbone lay-out, biogas from several digesters is collected through pipeline segments into a larger common pipeline, which in turn connects to the hub.^{9,10} The main function of the grid is biogas transport, but pipelines may also serve as a storage facility by means of line-pack storage; ie, a surplus of biogas can be stored in pipelines by controlling the pressures. If biogas is transported in a pipeline, the amount of biogas present in the pipeline depends on, among others, the dimensions of the pipeline and the pressure in the pipeline. When this pressure is higher, more biogas is present in the pipeline. The additional amount of biogas present in the pipeline, as a result of a higher pressure, is the line-pack storage volume.¹¹

Depending on the end use of the biogas, the potential value of biogas storage will vary. If a biogas network in a region is not connected to the main energy infrastructure, such a decentralized biogas network would require decentralized storage facilities to serve as a backup for balancing, in order to minimize the mismatch in time of supply and demand, and to buffer small fluctuations in supply.¹²⁻¹⁴ A necessary biogas storage volume is estimated to be 30–50% of daily production.¹⁵ When green gas is used as transport fuel, storage is part of the installation at the fuel station; in this case, the biogas is upgraded and compressed.¹³ By using a CHP, biogas could be used to facilitate the balancing of the local supply and demand of heat and electricity. Part of the imbalance may be caused by the intermittency of renewable energy sources like wind and solar.¹² Biogas storage can play a role in generating short-term balancing power and, to a certain limit, long-term balancing power.¹⁶ In a review article on biomethane storage,¹⁷ it was stated that biomethane “may play a pivotal role in optimizing the performance of integrated energy systems” (Budzianowski et al., 2017). The authors developed criteria and evaluated biomethane storage options from a technology point of view. Characteristics of business models for biomethane storage were described and sustainability aspects mentioned. One of the presented promising technological options for biomethane storage is storage within the biomethane generation infrastructure of piping. Quantitative data on costs or storage volumes in such infrastructure were not included.

Bärnthaler et al.¹³ give information, including costs, on biogas storage facilities ranging from atmospheric to high pressure (30 MPa) installations; attention was given to storage in the pipelines of a biogas distribution grid. It was concluded that the volume of the line-pack storage in case of a small grid is very limited. In another report, by Van Eekelen et al.,⁹ values for biogas storage costs

are given; from the table presented, line-pack has the lowest investment costs per cubic meter stored; no information on storage volume and assumptions are included. Weidenaar T. discusses the biomethane supply chain in his thesis and explains line-pack storage.¹⁸ His model addresses the volume of line-pack storage in natural gas distribution grids. This storage can be used if the capacity of a gas grid is insufficient for the injected biomethane. Line-pack storage costs are not explicitly dealt with.

Line-pack storage of gas in the natural gas grid was studied and modeled,¹⁹⁻²¹ including the interaction of line pack in natural gas grids and electrical energy generation from wind.^{22,23} Also, the economic value of line-pack in relation to large-scale energy production has been discussed²⁴⁻²⁷; line-pack in the natural gas grid can be seen as a flexibility tool.²⁸ The Dutch Transmission System Operator, Gas Transport Services, offers line-pack flexibility services to shippers who do not meet their daily balance criteria.²⁹

A biogas gas grid, however, differs considerably from the natural gas grid: The volumes of biogas to be transported and the transport distances are relatively small; the biogas is collected from several digesters to a hub.⁷ No study on modeling of line-pack storage in a biogas grid has been published before.

Recapitulating, a biogas transport grid could improve efficient use of biogas. Biogas can be utilized to optimize an integrated renewable energy system, where storage plays a crucial role. Biogas use as a decentralized source of energy requires storage, and line-pack storage in the biogas transport grid can provide this service. In the natural gas grid, line-pack storage has been shown to have economic value. This study aims at describing biogas line-pack storage in a model. This model gives insight into the line-pack storage volume and costs in a biogas transport grid. Thereby, it adds to the knowledge that can be used to assess the feasibility of a biogas collection infrastructure.

In Section 2, the line-pack storage model is presented. The model simulates the biogas line-pack storage in two lay-outs of a biogas grid that collects biogas from several digesters to a central collection point via pipelines, as presented in Hengeveld et al.⁷ Differences between biogas storage in a grid with separate pipelines, the star lay-out, and a grid with shared use of pipelines, the fishbone lay-out, are shown. Additionally, a method to explore the costs of enlargement of the line-pack storage volume in a grid is proposed. In Section 3, line-pack costs are compared to costs of other means of biogas storage.

2 | METHODOLOGY

The model description starts with an overview of the biogas transport model (Section 2.1). Then the line-pack

storage model is presented as an expansion of the transport model (Section 2.2). The model to simulate enlargement of the biogas line-pack storage is explained in the last section (Section 2.3).

2.1 | The biogas transport model

The biogas transport model⁷ describes costs and energy use for a regional biogas grid. The configuration comprises digester capacities (m^3h^{-1}), length of the pipeline segments (km), diameters of pipeline segments (m), and pressures (MPa) at the digester sites. Model input variables are region size (km^2), scale of (identical) digesters (m^3h^{-1}), and grid type. The volume of a gas is measured in m^3 at standard conditions (temperature 273.15 K and absolute pressure 0.101325 MPa).

Figure 1 shows the two grid types studied, “star lay-out” and a “fishbone lay-out” in an example with one hundred digesters and their square source areas. At the digester site, a compressor is installed to deliver the required transport pressure in the pipeline. The source area of a digester is related to the digester scale by a biogas production rate of $52 \cdot 10^3 \text{ m}^3\text{km}^{-2}\text{a}^{-1}$, based on Bekkering et al.³⁰

Results from optimization are minimal transport costs (€ct m^{-3}) with the associated configurations. The optimization of the biogas transport assumes the absolute pressure at the end user to be 0.101325 MPa and maximum allowable absolute pressure in the grid to be 0.9 MPa, ie, the maximum pressure according to Dutch regulations. Five pipeline diameters (m) with laying costs (€ km^{-1}) are

available to choose from in order to minimize biogas transport costs. A net present value (NPV) calculation is used to add the components of the total cost: pipeline investment costs (€) and operational and maintenance (O&M) costs (€ a^{-1}); compressor investment costs (€) and O&M costs (€ a^{-1}); and compression costs (€ a^{-1}), comprising the cost for energy use of the compressor. The assumptions and method to calculate biogas transport costs in a pipeline are similar to those used in previous studies^{1,7} and intended for an agricultural region in the Netherlands.

2.2 | Modeling line-pack storage

Figure 2 illustrates the model for biogas line-pack storage. The biogas transport model⁷ is used to determine the configuration (2) with minimal transport costs (3), from the input variables (1), this is the “transport-only condition.” The biogas volume present in a grid (4) is called line-pack,²⁷ measured in m^3 , under standard conditions, and can be found from the dimensions of the pipeline segments and the absolute pressure in the grid.¹¹

In a configuration with minimal transport costs, the maximum pressure in the grid is lower than the maximum allowable pressure, 0.9 MPa. Increasing pressure at the grid inlets at the digester sites increases energy use, cost per volume of biogas transported (€ct m^{-3}) and biogas volume (m^3) present in the grid; in this way, more biogas is available in the grid than necessary for transport only. The surplus biogas can be regarded as biogas stored

FIGURE 1 Grid configurations with fishbone lay-out (upper left) and star lay-out (lower right); the distance between digesters depends on the scale of the digesters⁷ [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 Flow chart of the model calculations for biogas line-pack storage; the graph labels in the results section correspond to the words in bold.

in the grid and is called line-pack storage. The increased cost as compared to the transport-only situation reveals the costs of line-pack storage. If in a simulation maximum pressure in the grid is increased to be equal to the maximum allowable pressure (5), the “transport-and-storage condition,” then the maximum line-pack storage (7) is reached.

The line-pack storage volume V_{lp} in m^3 of biogas for a pipeline segment is given by the volume difference between the two conditions,¹¹

$$V_{lp} = V_0 \left(\frac{P_{m,lp}}{K_{m,lp}} - \frac{P_{m,t}}{K_{m,t}} \right) \frac{1}{P_n} \frac{T_n}{T} \quad \text{with } V_0 = \frac{\pi d^2 \cdot 10^{-6}}{4} \cdot l \quad (1)$$

The dimensions of the pipeline segment are length l (m) and diameter d (mm). $P_{m,lp}$ (Pa) and $P_{m,t}$ (Pa) are the mean pressures in the pipeline segment for the line-pack condition and the transport-only condition respectively, while $K_{m,lp}$ (-) and $K_{m,t}$ (-) are the gas law deviation coefficients for these two conditions. T_n and P_n are the standard conditions of temperature and pressure; T is assumed to be 288.15 K.⁷ The formula shows that the line-pack storage volume depends roughly on the volume V_0 of the pipeline segments in the grid and on the difference in mean absolute pressure, $P_{storage} = P_{m,lp} - P_{m,t}$, between the transport-and-storage conditions and the transport-only conditions for each pipeline segment as $K_{m,lp} \approx K_{m,t}$.¹⁸

Total line-pack storage is calculated by summation of line-pack storage of each pipeline segment. Costs of

maximum line-pack storage ($\text{€ct h}^{-1} m^3$), ie, per m^3 stored biogas, can be deduced. The difference in “transport” costs (€ct m^{-3}) between the transport-and-storage and the transport-only configurations, together with the total grid capacity ($m^3 h^{-1}$), reveals the line-pack storage costs per hour (€ct h^{-1}) for the maximum line-pack volume (m^3). The costs per hour and per m^3 are found through dividing by the maximum line-pack volume (m^3). Line-pack storage costs ($\text{ct h}^{-1} m^{-3}$) are variable costs only, as no additional investments are needed. They are the additional compression costs to establish the higher pressure in the grid during 1 hour to accommodate the surplus $1 m^3$ biogas in the grid. This shows that annual line-pack storage costs depend on the total time of storage, ie, the sum of the cycle durations in a year.

As an example to illustrate Figure 2, consider a region of 738 km^2 , with 16 digesters of scale $300 m^3 h^{-1}$, using a fishbone grid lay-out with a total grid capacity of $4800 m^3 h^{-1}$. Using the biogas transport model transport costs are minimized by varying the diameters of pipeline segments. These minimal transport costs are 5.05 €ct m^{-3} , and the maximum pressure in the grid is 0.29 MPa . Increasing the maximum pressure in this grid to the maximum allowable pressure of 0.9 MPa increases costs to 6.36 €ct m^{-3} , an increase of 1.31 €ct m^{-3} ; ie, per m^3 biogas transported in the transport-and-storage condition. With a total grid capacity of $4800 m^3 h^{-1}$, line-pack storage costs per hour in the grid are 63.04 € h^{-1} . Maximum line-pack storage volume is $6501 m^3$. When this maximum is stored, costs to store one cubic meter of biogas for 1 hour are $0.97 \text{ €ct h}^{-1} m^{-3}$.

The transport model is based on steady state gas flow.^{11,24} The biogas storage model evaluates line-pack storage as a difference between two steady-state transport configurations and does not describe the transient phase of filling and withdrawal. When line-pack is applied, the biogas pressure at the grid outlet, ie, at the hub, is higher than without line-pack. In a fishbone lay-out, the pressure at the hub has one value at the end of the collecting pipeline segment. In a star lay-out, the pressure at the end user can be different for each individual pipeline, as the pipelines are mutually independent. For details of calculations, the reader is referred to Appendix A.

2.3 | Enlargement of line-pack storage

To enlarge line-pack storage, larger pipeline diameters are chosen compared to those found by minimizing costs in the transport model. Using pipelines with larger diameters reduces energy costs of biogas transport, because of lower pressures needed in the grid, but together with the

higher investment in pipelines, this is a suboptimal solution for the biogas transport. To what extent transport costs increase depends on the precise choice of pipeline segments whose diameters are enlarged and the size of this new diameter.

Obviously, a larger diameter implies a larger volume within pipelines. But in addition, a larger diameter of a pipeline segment in the grid reduces the pressure needed for biogas transport. The difference between the mean pressure for the line-pack condition and mean pressure for the transport-only condition is P_{storage} . Therefore, keeping maximum pressure at 0.9 MPa, the pressure difference in line-pack storage, P_{storage} , is larger when a larger diameter is used. A larger P_{storage} induces a larger line-pack storage, as described in Section 2.2.

A fishbone lay-out is generally shown to have the lowest costs for the main function of the grid, biogas transport.⁷ We suggest the following procedure to simulate enlargement of line-pack storage volume in such a grid, as illustrated in Figure 3. The procedure starts from the optimal transport grid dimensioning as described in Section 2.2. Then the maximum allowable pressure for the transport is lowered. Constrained with this lower maximum transport pressure, the configuration of the grid with lowest transport costs is determined. Generally, this grid has pipeline segments with larger diameters. Line-pack storage volume and costs are determined in the same way as in Section 2.2. The following paragraph explains the procedure in more detail.

The highest pressure in the grid at transport-and-storage conditions ($P_{\text{T\&S}}$) is the maximum allowable

pressure. In the line-pack storage model, $P_{\text{T\&S}} = 0.9$ MPa is used. In the transport-only condition, if the highest pressure in the grid needed for the transport-only condition is P_T and the maximum allowable pressure for transport-only is $P_{T_{\text{max}}}$, then $P_T < P_{T_{\text{max}}}$. In fact, P_T is a result of the cost optimization with restriction $P_T < P_{T_{\text{max}}}$. In Section 2.2, one value for the maximum allowable transport pressure is implemented, $P_{T_{\text{max}}} = 0.9$ MPa. As line-pack storage volume depends on the pressure difference, $P_{\text{storage}} = P_{\text{T\&S}} - P_T$, then the lowering of P_T with constant $P_{\text{T\&S}}$ makes the line-pack storage larger. A simulation with a lower maximum allowable transport pressure $P_{T_{\text{max}}}$ was carried out; this induced a lowering of the optimal maximum transport pressure P_T at the transport-only condition. The maximum allowable pressure needed for transport only was varied from $P_{T_{\text{max}}} = 0.9$ MPa downwards to $P_{T_{\text{min}}}$, thereby forcing the optimal maximum transport pressure P_T to report lower values, and use of larger pipeline diameters in consecutive simulations. $P_{T_{\text{min}}}$ is the lowest transport pressure possible, ie, the transport pressure in case all pipeline segments have the largest diameter. For each value of $P_{T_{\text{max}}}$, the conforming optimal transport grid is found with a value for transport pressure P_T , and for this grid, the line-pack storage is determined using $P_{\text{T\&S}} = 0.9$ MPa. The value $P_T - \delta$ is used as a starting point for the next simulation. The value δ determines the maximum difference in transport pressure between two different solutions; in this case, $\delta = 10$ Pa was used.

Extra costs for the enlargement of the line-pack storage can be deduced from the difference between the

FIGURE 3 Flow chart to simulate enlargement of line-pack storage by lowering the maximum allowable transport pressure. Fishbone lay-out; digester scale and total grid capacity known

transport costs (€ct m⁻³) in the suboptimal grid configuration, with $P_{T\_max} < 0.9$ MPa, and transport costs (€ct m⁻³) in the optimal configuration with $P_{T\_max} = 0.9$ MPa, in both the transport-only condition. This difference, the total grid capacity (m³h⁻¹), and assuming 8000 hours of biogas production per year (h a⁻¹) give fixed additional yearly costs (€a⁻¹). The variable costs of line-pack storage are modeled as in Section 2.2. Appendix A gives details of calculations.

2.4 | Additional assumptions

The transport of biogas in a grid needs a measurement and control (M&C) system. Especially in a grid with fishbone lay-out, pressures and flows in different parts of the grid are interdependent, and dedicated information and communication technology may be needed. Line-pack storage originates from an increase of pressure in a transport grid. M&C costs are attributed to transport of biogas; we assume that no additional M&C is needed for the line-pack storage.

Measurement is also needed for billing of biogas transported to a hub: quantity and quality of biogas delivered by each producer need to be known.³¹ As for biogas line-pack storage costs in a grid with fishbone lay-out, it may not be easy to allocate these costs to individual producers or end-users. Storage costs could be shared among stakeholders using a chosen key, eg, depending on the volume transported in a year. In a star lay-out, use of the individual biogas pipeline could be the responsibility of the producer using the pipeline, which results in lower transport costs for producers close to the end user and also differing values for line-pack storage costs. Billing of line-pack storage is not included in the model. We assume that biogas transport costs, and thereby line-pack storage costs, are shared by all producers, independent of distance from the producer to the biogas collecting point, ie, the hub. Business models need to be developed to support this type of cooperation among producers.¹⁰

3 | RESULTS AND DISCUSSION

Section 3.1 discusses results of the biogas line-pack storage model. A comparison is made for digester scales of 300 and 1200 m³h⁻¹ biogas. The lower scale is a relatively small digester, while the higher scale represents a moderately large digester.³⁰

The results for four moderate large digesters (1200 m³h⁻¹) can be compared with 16 small digesters (300 m³h⁻¹), as they have total source areas of identical size. In Section 3.2 costs of enlargement of the storage

volume in a grid with fishbone lay-out are presented. The enlargement is a result of using pipelines with larger diameters than those specified by the lowest biogas transport costs scenario.

3.1 | Line-pack storage costs

3.1.1 | Model results

Figures 4 and 5 give results for a grid with digester scales of 300 and 1200 m³h⁻¹, respectively, both for a fishbone lay-out and a star lay-out. The maximum volume of line-pack storage and associated costs per cubic meter biogas stored is shown.

Both Figures 4a and 5a show that for short-distance grids, the maximum storage is low, as a result of a relatively small pipeline volume in the grid. For a fishbone lay-out the longest-distance grid also has low storage opportunities; this is a result of the high pressure needed for transport, which is close to 0.9 MPa, so only a small increase in pressure is possible to accommodate line-pack storage. In the long-distance grid with a star lay-out, the biogas transport model showed that the choice for a pipeline with a larger diameter outweighs the increasing compression costs.⁷ As a result, the pressures needed for transport are lower and the total pipeline length is high. Therefore, a large grid with a star lay-out allows very high volumes of line-pack storage. For a squared source area with side of 95.1 km, a storage volume of 213·10³ m³ is calculated; this is shown in Figure 6. The line-pack storage costs (€ct m⁻³h⁻¹; Figures 4b and 5b) are similar for both grid types and decrease with increasing grid distance. One has to keep in mind that the costs for biogas transport in these large-distance grids with star lay-out are higher than in a fishbone lay-out because of the higher investment costs in pipelines; this is more pronounced for the scenarios with a digester scale of 300 m³h⁻¹.⁷

Comparing Figure 4A with Figure 5A shows that when the side of the region is 54.4 km, the maximum line-pack storage in a grid with digester scale of 300 m³h⁻¹ is larger than in a grid with digester scale of 1200 m³h⁻¹. The smaller digester scale requires more pipelines for the same region size and thereby supports the higher line-pack storage. In a star lay-out, the pressure drop in the individual pipelines for biogas transport is higher when the larger digester scale is implemented. The increase in pressure to the maximum allowable pressure in the simulation of the line-pack storage is therefore smaller. This also applies to the fishbone lay-out, but to a lesser extent. When the region sides are 27.2 km and 81.5 km, the maximum line-pack storage in a fishbone lay-out is lower and

FIGURE 4 A and B, Maximum volume (dashed) and costs (solid) for line-pack storage in a biogas grid with star lay-out (blue, triangle) fishbone lay-out (red, square); digester scale is $300 \text{ m}^3\text{h}^{-1}$. The labels show the number of digesters in the grid. [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 A and B, Maximum volume (dashed) and costs (solid) for line-pack storage in a biogas grid with star lay-out (blue, triangle) fishbone lay-out (red, square); digester scale is $1200 \text{ m}^3\text{h}^{-1}$. The labels show the number of digesters in the grid. [Colour figure can be viewed at wileyonlinelibrary.com]

of the same order of magnitude, respectively, for the two digester capacities.

As an illustration, we consider line-pack storage in for a digester scale of $300 \text{ m}^3\text{h}^{-1}$ and an area with a side of 54 km in a fishbone lay-out; the total biogas volume produced is $19.2 \cdot 10^3 \text{ m}^3\text{h}^{-1}$. The maximum storage is $32.4 \cdot 10^3$

m^3 ; this shows that a complete interruption of demand for around 1.5 h could be solved by line-pack storage when the line-pack storage is initially not in use. Once the storage is filled the costs for maximum line-pack storage, caused by increased energy use, are $0.49 \text{ €ct m}^{-3}\text{h}^{-1}$, ie, 158 € per hour resulting in 3.80 k€ for 24 hours.

FIGURE 6 Line-pack storage costs in a biogas grid with star lay-out (A) and a fishbone lay-out (B); digester scales are 300 and 1200 m³h⁻¹. The labels show the side of the squared source area in km. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 6 shows the total cost for line-pack storage per hour depending on the maximum line-pack storage volume for both grid types.

The model calculations for digester capacities from 100 up to 1800 m³h⁻¹ with steps of 100 m³h⁻¹ reveal that the costs of line-pack storage can be more than 2 €ct m⁻³h⁻¹ for small-scale digesters in a small grid, but these costs tend to be around 0.5 €ct m⁻³h⁻¹ for larger digesters and for larger grids; summarizing: storage costs range roughly between 0.3 and 1.5 €ct m⁻³h⁻¹.

Partial use of the maximum line-pack storage does not result in proportionally lower costs; costs per m³h are higher when less than the maximum is in use. The storage volume is by approximation proportional to the extra pressure,¹⁸ but the costs for increasing the pressure are lower if the absolute pressure is higher.⁸ When using line-pack storage, the pressure at the grid outlet, ie, the hub, increases as well. In some cases, the higher pressure reduces energy consumption of a connected apparatus, for example, when upgrading biogas to natural gas quality. In that case, net storage costs are lower than shown. If a reducing valve is used, the energy is wasted.

3.1.2 | Line-pack storage costs as compared to costs in other storage facilities

In this section, a comparison is made of line-pack storage costs with two other types of biogas storage. Pressureless gas storage is typically used for short-term storage, ie, several hours, and range from storage volumes of 500 to 2000 m³. Alternately, pressurized pipes can store from 60·10³ up to 250·10³ m³ of biogas.¹³ The comparison is not straightforward as the cost structure for the three types of storage are different. Use of pressurized pipes requires investment costs, operational costs, and charge

energy consumption, while the pressureless storage involves only investments and has negligible variable costs.¹³ Line-pack storage has only energy costs, as the investment costs for the grid are attributed to biogas transport. Table 1 gives a summary.

A comparison of annual storage costs per m³ biogas stored (€a⁻¹m⁻³) are shown for 1-year storage scenarios in Figure 7. The number of cycles per year (a⁻¹), ie, storage charge followed by discharge, and the duration (h) of cycles are varied. The number of cycles per year is on the horizontal axis; the maximal value shown corresponds with one charge-discharge per day. Costs of storage in pressurized pipes increase linearly with increasing number of cycles, but storage duration in each cycle has no influence. For line-pack storage, a similar effect is observed, but here also the duration of the storage cycle plays a role. Longer periods of storage increase annual costs, ie, dependency on the product of number of cycles with the duration (h) of one cycle. Costs of pressureless gas storage do not depend on the number of cycles. The graph illustrates these different cost structures.

Investment costs of pressurized pipes are estimated to be 2.0 M€, 3.8 M€, and 6.8 M€ for storage sizes of 60·10³, 125·10³, and 250·10³ m³, respectively; annual O&M costs are 2% of investment, and charge energy consumption for storage is 0.4 kWh m⁻³, adapted from

TABLE 1 Summary of costs structure for types of biogas storage

Biogas Storage Type	Variable Costs	Investment Costs
Pressureless gas storage	low to negligible	yes
Pressurized pipes	yes	yes
Line-pack storage	yes	no

FIGURE 7 Comparison of costs for line-pack storage with pressurized pipes and pressureless biogas storage for different sizes of storage facility. Example of line pack storage in a fishbone grid with digester scale $300 \text{ m}^3 \text{ h}^{-1}$ and total biogas production $19.2 \cdot 10^3 \text{ m}^3 \text{ h}^{-1}$; the duration of a storage cycle is 1, 2, 8 and 12 h. [Colour figure can be viewed at wileyonlinelibrary.com]

Weidenaar.¹⁸ Investment costs of pressureless gas storage are estimated to be 168, 119, 100, and 85 €m^{-3} for storage sizes of 500, 1000, 1500, and 2000 m^3 , respectively, with O&M costs of 1.5 k€ a^{-1} .¹¹³ NPV calculations with the same input data as used in the biogas grid calculation reveal the annual costs. The data for line-pack storage are presented, as an example, for a biogas grid with digester scale of $300 \text{ m}^3 \text{ h}^{-1}$, 64 digesters, and total biogas production of $19.2 \cdot 10^3 \text{ m}^3 \text{ h}^{-1}$. Maximum line-pack storage in this scenario is $32.4 \cdot 10^3 \text{ m}^3$. A line-pack storage cycle duration of 1, 4, 8, or 12 hours is shown. Duration of storage cycle does not affect costs for storage in pressurized pipes as it is assumed that only energy costs of charging contribute. In Figure 7, annual costs per cubic meter stored biogas are presented assuming that storage facilities are fully used in a storage cycle; obviously, partial use of a storage facility increases the costs per m^3 stored.

Pressureless storage is often applied to provide the necessary biogas storage volume of 30% – 50 % of daily production.¹⁵ For a stand-alone digester with a scale of $300 \text{ m}^3 \text{ h}^{-1}$, the required storage volume is 2100 to 3600 m^3 . The costs related to this storage could be seen as part of the biogas production chain.

Within the limitations of the models used, Figure 7 gives rise to some observations. If a biogas transport grid is used, the size of line-pack storage can be considerably larger than a single pressureless storage facility. In the example, the storage in the biogas transport grid can accommodate from 16 to 65 pressureless storage facilities depending on the size. The line-pack storage can compete on costs with pressureless storage; this is more pronounced if storage is infrequently used for short cycle duration. Storage once a day could reflect the storage needed to balance supply and demand because of lower demand during the night. The duration of such a storage

could be around 8 hours; the order of magnitude of line-pack and pressureless storage correspond. Moreover, line-pack costs may have an advantage of showing lower costs if on some days the duration of the storage is lower and vice versa.

In line-pack storage, a single storage cycle with duration of 6 months has similar annual storage costs as 12 hours of storage on a day during 1 year. Thereby, high annual storage costs, more than $20 \text{ €a}^{-1} \text{ m}^{-3}$, are involved. Therefore, month-long line-pack storage is not recommended. If properly dimensioned, pressurized pipes are suggested for month-long storage times, where annual costs are estimated to be 4 to $5 \text{ €a}^{-1} \text{ m}^{-3}$, depending on the scale of the facility. These costs are still high as compared to the production cost of the biogas¹ and give the order of magnitude of additional costs of seasonal balancing using biogas storage.

A benefit with line-pack storage is that it does not need additional investment, thereby financial risks are lower as compared to the other methods of storage. On the other hand, line-pack costs are equivalent to energy costs; meaning that the use of line-pack storage reduces the overall efficiency of renewable energy production.

3.1.3 | Sensitivity to costs of electricity

Data on sensitivity of the biogas transport costs on model parameters are presented in Hengeveld et al.⁷ The line-pack storage model assumes that no additional investments and variable storage costs consist of extra compression costs. Therefore, the costs of line-pack storage vary proportionally with the costs of electricity, if the same pipelines are used in the grid.

However, variation in electricity costs can change the choice of diameter of the pipeline segments in the minimization of transport costs; for example, a larger diameter of the pipeline is encouraged when the electricity costs increase. As a result, the storage volume increases and the costs of storage (in €ct m³h⁻¹) is smaller than what would be expected based on a linear proportionality.

3.2 | Enlargement of line-pack storage

The method proposed in Section 2.3 is applied to a grid with a fishbone lay-out. In an example of the results, the maximum allowable transport pressure P_{T_max} is on the horizontal axis of the graph in Figure 8. Figure 8a shows the increase in line-pack volume with decreasing

FIGURE 8 Line pack storage enlargement by lowering the allowed transport pressure. Line-pack storage volume (A) and transport costs (B). Fishbone grid with 64 digesters with scale of 300 m³h⁻¹, ie, total grid capacity is 19.2·10³ m³h⁻¹ [Colour figure can be viewed at wileyonlinelibrary.com]

P_{T_max} . As P_{T_max} decreases, a different choice of pipeline diameter for the pipeline segments needs to be applied; in general, the pipeline diameter increases. The lowest value of the maximum allowable transport pressure P_{T_max} resembles the case where all pipelines in the biogas grid have the largest diameters; a lower pressure than that prevents the grid from accommodating biogas transport from digesters to hub. This also limits the potential for investment in larger diameter pipelines.

From the transport costs shown in Figure 8B, the line-pack storage costs can be retrieved. The green line gives the lowest biogas transport costs, the lowest costs at a maximum allowable transport pressure of 0.9 MPa. The red line shows the increase in transport-only costs as a result of a different choice of the pipeline diameter for the pipeline segments, induced by the restriction of a lower transport pressure. The difference between the red and the green line is used to calculate the fixed annual additional costs for the change to larger pipeline diameters in the pipeline segments. The blue line shows the transport costs for the transport-and-storage condition. From the difference between the blue line and the red line, the variable costs of the line-pack storage are calculated, in the same way as described in Section 2.2.

The results are summarized in Figure 9 for digester scales of 300 and 1200 m³h⁻¹ in the same sized region. The variable storage costs and the storage volume are presented as a function of the fixed annual costs. Data as shown in the figure can be used to estimate the costs of line-pack storage needed. The highest value of the fixed annual storage cost reveals a situation in which the diameters of all pipeline segments have the maximum size. The grid with digester scale 300 m³h⁻¹ has more length of pipeline; therefore, a larger line pack storage is possible, up to 112·10³ m³, an increase of 72·10³ m³ due to maximum diameter enlargement of pipeline segments. However, the extra fixed annual costs become extremely high, 2.4 M€ a⁻¹, ie, 30 € m³a⁻¹. The variable costs of line-pack storage measured in €ct m³h⁻¹ show a decrease with increasing fixed storage costs.

In Table 2, the lowest fixed annual storage costs per increased line-pack storage volume, ΔV_{lp} (m³), are presented. Graphically, these represent the maximum slope of a straight line from the intercept to the points on the storage volume line. This maximum is found at relatively low values of the fixed annual costs. The order of magnitude of these annual fixed costs is similar to the costs of pressurized pipes and lower than the fixed costs of pressureless storage. Use of the increased line-pack storage volume requires variable storage costs that are slightly lower as compared to the storage costs in the optimal

FIGURE 9 Enlargement of line-pack storage. Line-pack volume and variable costs as a function of the fixed storage costs. Fishbone grid with total grid capacity of $19.2 \cdot 10^3 \text{ m}^3 \text{ h}^{-1}$; side of the region is 54.4 km [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Line pack storage costs at minimum annual fixed storage costs per m^3 extra storage volume based on Figure 9

Digester Scale $\text{m}^3 \text{ h}^{-1}$	Fixed Storage Costs k€ a^{-1}	ΔV_{lp} $10^3 \cdot \text{m}^3$	Fixed Storage Costs per m^3 $\text{€ m}^{-3} \text{ a}^{-1}$	Variable Storage Costs per m^3 $\text{€ct m}^{-3} \text{ h}^{-1}$	
				enlargement	no enlargement
300	34	9.54	3.6	0.472	0.488
1200	112	13.1	8.5	0.571	0.639

Note. ΔV_{lp} is the increase in line-pack storage.

transport grid, ie, with no pipe diameter enlargement. This shows that a small extra investment in the biogas transport grid could be financially sensible, as to make use of line-pack storage potential, instead of investment in other storage facilities. Detailed analysis of biogas storage scenarios, as suggested in Section 3.1.2, is needed to assess feasibility.

4 | CONCLUSIONS: FUTURE RESEARCH

A model was developed to describe the line-pack storage of biogas in a dedicated transport grid. The model calculates maximum line-pack storage volume and the storage costs depending on the digester scale, the total grid capacity, and the grid lay-out. The storage costs originate from extra energy compression costs: line-pack storage does not require additional investment in the transport grid.

Generally, the storage volumes are larger when the grid consists of small-scale digesters. In a small region, with a small total grid capacity, line-pack storage is small. In a grid with a fishbone lay-out, the line-pack storage is also small in a large region, as a result of the small

differences in pressure for transport and the maximum allowable pressure in the grid. In a large region, the maximum line-pack storage volume in a star lay-out is relatively high, but transport costs are high as well.

The model shows that storage costs are roughly between 0.3 and 1.5 $\text{€ct m}^{-3} \text{ h}^{-1}$. The storage costs thereby depend on the duration of the storage and do not depend on the number of charge/discharge cycles. The costs are based on steady state calculations and apply when the maximum volume of line pack is used.

Line-pack storage can compete with pressureless storage on costs for short-term storage, but pressurized pipes are preferred for seasonal storage. Line-pack storage costs depend on the duration in storage time and are shown to be suitable to accommodate for daily fluctuations of supply and demand.

A method to study the effects of the enlargement of the line-pack storage was proposed. The enlargement was simulated by lowering the maximum allowable pressure needed for transport. The scenario analysis shows that in a grid with fishbone lay-out, only a relatively small enlargement of the line-pack storage would be possible.

Energy storage plays a role in balancing supply and demand. Therefore, quantification of costs and volume

of the line-pack storage makes it possible to assess to what extent the line-pack storage can be deployed for this task. Further research could aim at modeling more complex grid types, eg, a combination of star lay-out and fishbone lay-out. Another task would be to simulate line-pack storage use in a biogas grid in order to supply flexibility in electricity production. The dynamic aspects of charging and discharging line-pack storage are not included in our study and could be investigated.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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APPENDIX A

The Supporting Information gives details on using the biogas transport model for calculation of line-pack storage