MSc in Logistics & Supply Chain Management
Author: Michael Binnerup
Internship: Blue Planet Innovation APS
Date: 01-09-11 – 08-11-11

The Ringkøbing-Skjern Model

The biogas pipeline determination problem

HANDELSHØJSKOLEN
AARHUS UNIVERSITET

Blue Planet innovation

VIDENCENTRET FOR LANDBRUG

Table of Contents

1. Introduction **2**

2. Problem statement **2**

3. Delimitations **3**

4. The Ringkøbing-Skjern Model **3**

4.1. Project status **4**

5. Locating the Pipeline **5**

5.1. Network purpose - What to do with the Biogas? **5**

5.1.1. Upgrading the biogas to natural gas 6

5.1.2. Using biogas in the power plants 9

5.1.3. Conclusion on network purpose 16

5.2. Pipeline modelling in practice **17**

5.2.1. Step 1 - Main Pipeline 17

5.2.2. Step 2 - Slurry Pipelines 21

5.2.3. Step 3 - Connection Pipelines 22

6. General Applicability **22**

7. Future research **22**

Bibliography **24**

Appendix 1 .... **26**

Appendix 2 .... **27**

Appendix 3 .... **28**

Appendix 4 .... **29**

Appendix 5 .... **30**

Appendix 6 .... **31**

Appendix 7 .... **32**

Appendix 8 .... **33**

Appendix 9 .... **34**

Appendix 10 .... **35**

Appendix 11 .... **36**

Appendix 12 .... **37**

Appendix 13 .... **38**

Appendix 14 .... **39**

Appendix 15 .... **40**

Appendix 16 .... **41**

1. Introduction

CEESA Research shows that Danish economics will benefit from being independent of fossil fuels in 2050, since it's estimated that the sustainable energy sector will create up to 20.000 new workplaces all over Denmark, from now on and until 2020.

The same professors estimate that with the right timing Denmark could 3 or 4 double the energy export while reducing CO_2 emissions by 70% in 2030 compared to 1990, and thereby increasing social healthiness due to less air pollution (Lund, Morthorst, Mathiesen, & Meyer, 2011).

As an initiative Ringkøbing-Skjern municipality has a vision on being 100% sustainable in 2020. By concentrating on different sustainable solutions, such as adding additional insulating material to public buildings, construction wind and solar facilities, along with VE-gasses such as biogas and bio fuels facilities for transportation, the municipality is working towards their target (Ringkøbing-Skjern Kommune, 2011).

2. Problem statement

The purpose of this rapport is to describe and understand the activities in Ringkøbing-Skjern municipality, as well as giving an objective advice on which opportunities should be pursued to reduce costs while turning green.

This rapport will as well provide decisions makers with a framework for building the pipeline, given by the outcome of the advice.

3. Delimitations

- As from the problem statement this rapport will provide the reader with the tools for building solutions to the pipeline location problem, not a final result for implementing.

- Power plants often have more energy sources than gas to produce from. To reduce model complexity gas and only gas will be investigated.

- This rapport will not focus on the financial part of building the pipeline as well as the dimensioning and capacity calculations of the pipeline.

- CO^2 reduction calculations as well as biofuel for transportation will not occur in this rapport.

4. The Ringkøbing-Skjern Model

The project in Ringkøbing-Skjern is untypical in various ways compared to similar biogas projects. First of all decentralized way of thinking is quite unique due to the idea of pumping the slurry from the farm to a closely located common biogas plant owned by a cluster of farmers, trying to minimize transportation costs. Typically a tank truck transports the slurry to a rather big central biogas facility, which is considered costly since slurry contains large amounts of non-putrefying fluids such as water, which thereby is superfluous in the gas production process.

Another remarkable difference is the waste handling, distributing the degassed slurry back in a pipeline to the farmer, and using it as fertilizer. Along with the waste handling in place, the degassed slurry also doesn't in comparative pollute the subsoil water for drinking.

The last remarkable variation is the co-operative society of farmers, power plants, small and medium sized planning and construction companies, as well as the local industry to interacting trying to reach a common goal to become 100% sustainable.

4.1. Project status

Dansk Gasteknisk Center (DGC) suggests that the pipeline should be build in stages to be able to monitor and test different scenarios while building, to be able to adapt to get the best final result. DGC comes up with the following two stages for constructing the network that supplies the power plants with biogas (Jensen, Establishment of a biogas grid and interaction between a biogas grid and a natural gas grid., 2011).

Stage 1 involves:

- 5 biogas plants
- 5 million m^3 of methane
- 1 power plant
- 35 km of gas grid

Stage 2 involves:

- 60 biogas plants
- 60 million m^3 of methane
- 11 power plant
- 120 km of gas grid
- 2 gas compressors
- 2 upgrading units

These stages as shown above are only a piece of advice, and could thereby easily be broken up to even more stages which could be preferable due to that fact that stage two is remarkably bigger and more costly to implement that stage one.

5. Locating the Pipeline

In addition to these building stages the pipeline determination problem has two significant variations, each with different model specifications and procedures to solve the problems. Therefore the stages might appear different with respect to the chosen pipeline variation.

The first variation is a pipe that connects the power plants to supply them with biogas, as a substitute to natural gas. Alternatively the pipe is used to collect the biogas with respect to upgrade the entire biogas potential in the municipality. The last option is especially in interest to Energinet.dk, HMN Naturgas I/S and DONG Energy, since they administrate the Danish natural gas network, which might be without, or with a minimum of influence, if not being proactive to secure their future business as the natural gas runs out.

The unique part of both models in the network structure is the distribution of slurry from the farm to the biogas plant.

Usually a tank truck has done the slurry collection, which is to be considered rather costly and provided the bio plants with batches of slurry instead of a steady stream. To create flow and to try to bring down costs of warehouses (slurry tanks) the pipeline provides the biogas plant with slurry from the farms slurry tank when needed instead of having a buffer at the biogas plant.

5.1. Network purpose - What to do with the Biogas?

To determine how the pipeline network structure should look like, the purpose of the network is crucial. The network structures and the framework used to solve the problem are therefore dependent on what to do with the biogas and who to supply.

Form an objective perspective as mentioned in section 5, there is two options after collecting and producing the biogas.

1. Even the biogas is upgraded and transferred into the natural gas network, which means that the power plants renders is superfluous if no political amendment is made. The profit earned from transferring biogas could be used as funds for research in other sustainable power and heating technologies such as solar, wind and geothermal heat.

2. Or else the biogas is used as green-fuel in the power plants as a substitute to natural gas thereby heating Ringkøbing-Skjern municipality with green-heat while making green electricity.

5.1.1. Upgrading the biogas to natural gas

When all the biogas within the municipality is upgraded and transferred to the natural gas network, the problem is to minimize the costs of connecting the farms to biogas plants and the biogas plants to a central upgrading station. This problem is similar to J. R. Birge and V. Malyshko's designing problem in solar power system, where a number of heliostats are connected to a microprocessor. A number of microprocessors are then connected to a central computer that monitors the heliostats through the microprocessors (Birge & Malyshko, 1985). The practical tasks can as well here be modelled as a p-median problem, where P facilities related to a set of customers are located, such that the sum of the shortest distance in the weighted graph between customers and facilities is minimized. As in the solar power system additional constraints need to be added to the problem. To solve the pipeline location problem a branch-and-bound procedure may be useful if the number of facilities to be connected is small. Otherwise a heuristic algorithm described by the very same authors can be used.

The pipeline location problem with respect to upgrading the biogas to natural gas is also similar to the capacitated tree problem in which a minimum spanning tree is found where the sum of weights in any sub tree should be no greater than the capacity. In contrast to the tree approach our pipeline problem is allocating and directly connecting the farms to the biogas plant, and therefore several branches may not join it as if it was a spanning tree. This can be dealt with by adding constraints to the p-median problem as mentioned above.

5.1.1.1. Upgrading technologies

Biogas consists of methane (CH_4) and coal dioxide (CO_2). When upgrading the biogas the CO_2 is either removed or converted, which increase the flaming-value. The conversion technology isn't approved so far, therefore CO_2 removal will be the only technology considered in this rapport. The suggested is therefore that the CO_2 is to be removed, by one of the three following leading technologies[1].

1. Pressure Swing Adsorption (PSA)
2. Physical absorption – Water Scrubbing Facility
3. Chemical absorption – Amin Washing Facility

PSA and Water Scrubbing Facilities are preferable in Denmark (Jensen, Biogas til nettet, 2009).

Determining the flaming-value the Wobbeindex is used. With reference to the Danish gas regulations, natural gas should have a Wobbenumber between 50,8 and 55,8 MJ/m^3(n). Biogas (65 % CH_4 and 35 % CO_2) has a Wobbenumber at 27,3 MJ/m^3(n), in contrast to pure Methane with a Wobbenumber on 53,5 MJ/m^3(n).

Whenever upgrading the biogas the methane level increases from 65% to approximately 97,3%. At this methane level the gas has a Wobbenumber high enough, to burn equally good as natural gas. If the methane level in the gas is lower than the desired 97,3% after upgrading, propane is added to allow it into the natural gas grid (Jensen, Biogas til nettet, 2009).

5.1.1.2. Costs of upgrading

The costs of upgrading biogas are seen in Table 1 , which is based upon supplier information. The numbers are calculated under the assumptions of a biogas production of 5,6 million m^3 biogas each year, with an operating time of 8300 hours corresponding to 675 m^3/h. In the production, biogas consisting 65% methane is used (Jensen, Biogas til nettet, 2009). It is notable that the costs of

[1] For further information on the upgrading technologies see (Jensen, Biogas til nettet, 2009)

upgrading will decrease in time with an increase in capacity due to economies of scale.

Costs of Upgrading	Propane added	No Propane added	
PSA Facility	1,13	0,88	DKK/m3
Water Scrubbing facility	1,09	0,85	DKK/m3

Table 1 (Jensen, Biogas til nettet, 2009)

According to Dansk Gasteknisk Center (Jensen, Biogas til nettet, 2009) the Danish biogas quality appears rather high, and therefore it seems reasonable that no propane will be added, and the costs of upgrading therefore will be 0,88 DKK and 0,85 DKK.

5.1.1.3. Profitability in upgrading

Looking at the profitability when deciding to upgrade, the biogas/natural gas relationship needs to be considered. Table 2 below shows the flaming value and the associated cost when buying 1 Nm^3 of gas.

	Flaming value	Average Price/Nm3 in 2009
Naturalgas, kWh/Nm3	12,15	DKK 3,88
Upgraded biogas, kWh/Nm3	12,15	DKK 4,83
Biogas, kWh/Nm3	11,06	DKK 4,12

Table 2 (Jørgensen, Barmarksvæker, 2011)

Looking at the price relationship the average natural gas price is equal to 3,88 DKK/Nm^3. The price of biogas faced by the power plans is estimated to be 4,12 DDK/m^3 of methane where the price of biogas upgraded to natural gas quality is at 4,83 DKK per m^3 of methane (Jensen, Establishment of a biogas grid and interaction between a biogas grid and a natural gas grid., 2011).

The difference in price between the biogas before and after upgrading is equal to 0,71 DKK, which is markedly lower than the lowest cost of upgrading seen in Table 1 . To break-even the costs of upgrading must therefore be lower than 0,71 DKK. In other words the upgrading technology must be more efficient to become generally accepted as an alternative to regular biogas or natural gas. Otherwise the upgrading facilities must at least have a certain size to try to reduce upgrading costs to break even by having economy of scale as mentioned above.

Again comparing the prices between biogas and natural gas, biogas is 6% more expensive to produce from than natural gas. On the other hand upgraded biogas is 20% more expensive than natural gas seen in Table 3.

	Flaming value	Price
Relationship natural gas/biogas	1,10	0,942
Relationship Natural gas/Upgraded biogas	1	0,803

Table 3

In other words, upgrading biogas isn't efficient at the moment, due to the fact that the upgrading costs exceed the value added to the gas, as well as the circumstance that upgraded biogas is lead into the natural gas pipeline, and sold as natural gas at the natural gas price level which gives a negative profit due to the higher production costs as mentioned.

A way to deal with this negative profit could be to certify every m^3 of upgraded biogas lead in to the natural gas pipeline. This initiative might need Danish governmental or even EU attention. In the model it's therefore assumed that upgrading biogas isn't an option, since it's expected that it will take a while before implemented due to the bureaucratic procedures.

With an initiative like this the consumer of the gas (power plants, companies or households), can buy this "green certificate" to gain a green profile and thereby make the upgraded biogas break even and in that way an alternative to natural gas.

5.1.2. Using biogas in the power plants

Locating the pipeline for supplying power plants is in some points similar to the biogas-upgrading problem described in 5.1.1. Connecting the farms to the biogas plants is exactly the same issue as in biogas-upgrading problem, but instead of connecting the entire biogas plants to a single point, which could be the upgrading station as seen above, a biogas plant must be connected to the network (Main pipeline) that connects the power plants. This connection can even be directly to a connection point at the main pipeline or via another biogas plant located closer to the connection point.

Locating the pipeline is therefore done in three steps, since we're dealing with three levels of networks.

First the main pipeline is to be determined. Considering the minimum spanning tree may solve this part of the problem. (Balakrishnan & Render, 2007) Whenever the pipeline between all the power plants is set up, next step is to connect the farms with the biogas plants and then the biogas plants to connection points in the power plant network.

From the fact given in section 4 that the farmers are financially attached to a single biogas plant, locate the slurry pipeline that is connecting a cluster of farms, to a biogas plant is done by a minimum spanning tree framework, looking isolated at the individual biogas plant and the attached farms. The spanning tree is used to minimize the distance and thereby the costs of the pipeline. Since there is more than one biogas plant in the model this procedure will be repeated for every biogas plant.

After connecting the farms to the respective biogas plants, the last step is to connect the amount of new spanning trees to the main spanning tree that connects the power plants.

Since there is more than one connection point that has to be considered in the model, the framework from the biogas-upgrading problem needs to be reassessed.

To be able to solve the problem, sub-problems need to be formulated. Looking isolated at a part of the main pipe is therefore crucial to obtain optimality. This course of action is as well consistent with the fact that the pipeline is built in stages as mentioned in 4.1, and it's therefore natural to look isolated at the piece of pipeline that is about to be built within the current stage of the project.

Whenever a biogas plant is connected to the closest point of the main pipe, this point needs to be shifted to seek for optimality as shown in Appendix 1.

5.1.2.1. Biogas as a substitute to natural gas

From an economical perspective only, biogas wouldn't stand a chance against natural gas as an alternative without exemption of taxes, since natural gas is more efficient in the heat and electricity production process, and has a remarkably lower m^3 price at 1,20 DKK on average without taxes[2].

With the biogas tax exemption, and the perspective that natural gas is a limited resource, in contrast to biogas, which is renewable, biogas gets its raison d'être in heating villages along with geothermal and solar heating, thereby becoming more green by reducing CO_2 and waste as aimed for.

A remarkable factor that pleads for using biogas to heat households in the future is that a motor or kettle already running on natural gas today, don't need any significant modifications to produce electricity and heat when fuelled with biogas (65% methane). Thereby the Ringkøbing-Skjern municipality don't need to close the power plants and build green facilities such as solar plants, if no political amendment is made.

As a marked power consequence as the natural gas runs out, the prices of natural gas will increase, which will affect the operational costs at the individual power plant. Since the power plant is operating after the "pay for itself" principle, which means that it can't earn a profit and that all costs should be paid by the user, switching to an alternative energy source will in addition to the easy fuel switch be beneficial to keep down the operational costs and thus lower heating prices in the medium or long run, even though that the heating prices faced by the consumer will be higher compared to using natural gas in the first period of time.

---

[2] See: "Natural gas prices" sheet in "Assignment.xlxm"

This medium/long run effect is based upon a believe that biogas price will drop in the nearest future, as the biogas production technology as well as upgrading technology gets more efficient due to increased production experience. The price might rise again as a marked power consequence due to supply and demand changes when natural gas is about to run out.

Looking isolated at the heat demand faced by a power plant, the seasonality is remarkable as shown in Figure 1 . The demand in the summer period may cause some problems due to large gas tank needs in the closed network, since the biogas supply do not fluctuate over the year as mentioned earlier, in contrast to Natural gas that is supplied in the needed amount.

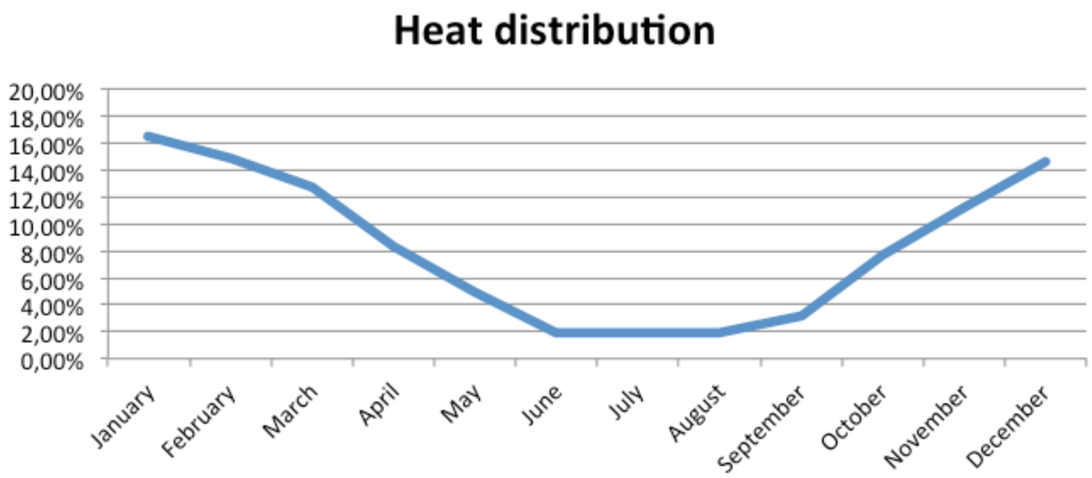


Figure 1 (Energi styrelsen, 2010)

This closed system issue along with the fact that biogas and natural gas have different flaming values as mentioned in Table 3, raises a need for analysing the supply along with biogas warehousing. For this analysis a production plan will be executed with benchmark in 2009 as production year converting the used natural gas into biogas, to see how sensitive the power plant is to the change, and what this closed system issue means.

Skjern Fjernvarmecentral will be used as representative for all the natural gas consuming power plants in the municipality since it is considered to be average in production size as from their annual rapport (Skjern Fjernvarmecentral

A.m.b.a., 2010), it's stated that Skjern Fjernvarmecentral has 3112 users, and annual heat sales of 67.605 MWH[3].

Whenever making a production plan the power plant have various strategies to produce after. The most common strategies used is a marked driven or the three step tariff shown in the scenarios below.

The main purpose of a power plant is as mentioned, delivering heat to the households in a single city and the surrounded areas. To produce the needed heat the power plant has two different opportunities. Even the power plant can produce on their kettle, which provides them with approximately 95% heat and a loss of 5%, or the power plant can run on motor and gain approximately 40% electricity, 55% heat and a loss of 5 % in the production process. (Skjern Fjernvarmecentral A.m.b.a., 2010)

As from the delimitations the scenarios will only concentrate on the heat produced from gas to minimize the models complexity.

In both scenarios 5 farmers is providing the biomass, which gives approximately 5 million m^3 of biogas each year (Jørgensen, Biogas omregner, 2011). The break-even price is set to 300 DKR. The initial biogas storage is set to 0 and the storage limit is set to 8000 m^3.

5.1.2.1.1. Scenario 1 – Following the marked with buffer tank strategy

The marked following strategy is characterized by calculating the power plants break-even price whenever producing electricity, to make sure that electricity production doesn't affect the heating price negatively. Therefore the power plant will only produce power in the time periods where electricity prices are higher than the break-even price.

[3] See "Main data" and "Skjern Fjernvarmecentral data" sheet in "Assignment.xlxm"

The electricity prices follow an electricity exchange, which is updated two days ahead. This means that the power plant can plan how to produce the needed heat at least one day ahead.

Since the gas supply is limited a buffer tank with hot water is used get more flexibility in the production, and to be able to produce electricity when favourable.

5.1.2.1.2. Output from Scenario 1

Looking at the usage of biogas in Appendix 2, we see that additional biogas is needed during the first and last months of the year. This problem can be solved in two ways. Even by adding more farms and thereby biogas supply to the individual power plant to provide them with the needed biogas in the winter period. This is of cause no good solution since the number of farms is also limited and as well will course in large amounts of excess gas in the summer period looking isolated at a single power plant. Considering Appendix 3, we see that a in the summertime, with the setting of 5 farms, a power plant with the maximum allowed biogas warehouse will have enough excess gas to fill approximately 3 warehouses.

A better solution is therefore to build large underground warehouses in a salt horst, which basically is a cavity in the underground[4]. In this way large amounts of gas can be stored in the entire system and provide the power plants when needed and thereby smoothen out seasonality.

Looking at Appendix 4 we see as expected that the kettle approximately follows the heat distribution as given in Figure 1 and that the motor follows a sine wave.

5.1.2.1.3. Scenario 2 – Three-step tariff with buffer tank strategy

The other most common production strategy is the Three-step tariff shown in Table 4. In contrast to the marked driven strategy the Three-step tariff strategy produces whenever peak load occur. In high load periods the strategy is marked

[4] For further information: http://gaslager.energinet.dk/DA/Om-gaslageret/Sider/default.aspx

driven, and production is triggered when the electricity price is exceeding the break-even price. In low load periods production isn't considered.

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00 - 06:00							
06:00 - 07:00							
08:00 - 12:00							
12:00 - 21:00							
21:00 - 24:00							

Peak load: High electricity price
High load: Medium electricity price
Low Load: Low electricity price

Table 4

5.1.2.1.4. Output from Scenario 2

Comparing the biogas output in scenario 2, shown in Appendix 5, with scenario 1, shown in Appendix 2, it's on one hand remarkable that when producing after the three-step tariff strategy the curve looks more even and controlled. On the other hand the seasonality issue is still unsolved and as shown in Appendix 6 excess gas reaches the same levels as in scenario 1.

Looking at the production output in Appendix 7 the motor sine wave gets more distinct due to a more controlled process. The kettle is also still following the heat demand distribution but also in a smoother manner.

5.1.2.2. Selling the excess biogas

Calculations from Aarhus University show that the biogas potential in Ringkøbing-Skjern municipality is estimated to be 37 million m^3 of methane a year (Olesen, 2009). To ensure that the biogas is living its full potential, additional marketing possibilities is needed, since it's unsure that the power plants are able to use the entire amount of biogas.

Companies such as "Arla Foods" in Videbæk and "Skjern Papirfabrik" in Skjern is some of the heavy consumers of energy in the municipality and has on the face of it, as steady gas demand all over the year, and could thereby in theory take a great amount of the excess biogas. Both companies have their own power plants implemented at the factory, which makes them highly interesting in this context.

"Arla Foods" already have plans of producing biogas themselves to obtain a green company profile[5].

Choosing not to cooperate with "Arla Foods", the limited slurry resource in the Videbæk area will be subject to heavy completion. In one hand this is of cause beneficial to the farmers in the area, since the slurry will be sold to the highest bidder. On the other hand competing might lead to unnecessary high raw material prices, which will affect the profitability in producing biogas. Having in mind that biogas already is an expensive gas to produce from, mentioned in Table 2 fighting over the raw material isn't preferable to disseminate biogas as a generally accepted source of energy.

Thus it might be beneficial among all parties to cooperate, even by dividing the slurry equally in the Videbæk area, or simply to connect "Arla foods" along with "Skjern Papirfabrik" to the public pipeline, supplying them with the needed biogas, and in this way kill two birds with one shot, since this solution probably will solve the seasonality problem along with the limited raw material problem.

5.1.3. Conclusion on network purpose

It is concluded that upgrading biogas isn't efficient at the moment due to fact that the cost of upgrading exceeds the value added to the gas. It's also concluded that upgrading is a possibility in the future, if the right conditions occur, such as addition green-gas contributions or a green-gas certification arrangement. The cost of upgrading might as well become subject to changes in the future due to economy of scale and increased experience in the upgrading process. It's

[5] http://aoh.dk/artikler/arla-investerer-kvart-milliard-i-videbaek-omraadet

therefore concluded that an upgrading network isn't profitable to build within the present conditions.

Using the biogas to supply power plants is on the other hand a more favourable solution, since the power plants doesn't need any remarkable changes in their production equipment to produce from biogas instead of natural gas.

It is also concluded that using biogas will, in the beginning, have a negative effect on the operational costs for the individual power plant, but provide the power plant with a long run advantage both on the operational cost side as well as the CO_2 emission and waste reduction side.

It's also remarkable that this solution still has some difficulties that need to be solved in order to reach the full network potential. It's in this context concluded that the warehousing issue is a relevant topic in all scenarios and that it needs to be solved.

Overall the pipeline network would have largest positive effect on supplying the power plants compared to upgrading.

5.2. Pipeline modelling in practice

As from the delimitations, this part of the rapport doesn't provide the reader with a full detailed solution for the overall Ringkøbing-Skjern pipeline problem. However this section presents the way of thinking in building the modelling tools for making a feasible optimal solution.

5.2.1. Step 1 - Main Pipeline

The Ringkøbing-Skjern Project assumes, as mentioned in 5.1.3 that the produced biogas should be distributed from the individual decentralized biogas plants in the municipality, to the power plants.

The biogas potential is evenly spread over the municipality as mentioned 5.1, but as seen in Appendix 8, the majority of the power plants are located in the northern part of the municipality. This will lead to a transportation need from south to north via a pipeline.

As mentioned in 5.1.2 the main pipeline problem can be solved by a minimum spanning tree approach. The Minimum Spanning tree problem, is given by a graph G=(V,E) with a weight on each of the edges (c). The objective is to find a spanning tree of edges of G with minimum total weight of its edges. The problem is solved by a greedy method that orders the edges according to non-decreasing weight and selects them in this order unless the next edge in the order makes a cycle with the previously selected edges, in which case it is not selected. (Stougie & Canzar, 2011)

In this context the objective is to minimize the length of the edges in the tree, given by the Euclidean distance formula $(x, y) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$, first used by Boruvka (Boruvka, 1926) to find the most economical construction of an electricity network in Moravia. The edges are given by the following mathematical formulation, where we use the notation $E(S) = \{\{i, j\} \mid i \in S, j \in S\}$ for all edges entirely inside a subset S of the nodes:

$$min \sum_{e \in E} c_e x_e \ (1)$$

s.t.

$$\sum_{e \in E} x_e = n - 1, \forall \subset V, s \neq \emptyset, V \ \ (2)$$

$$\sum_{e \in E} x_e \leq |S| - 1, \forall \subset V, s \neq \emptyset, V \ \ (3)$$

$$x_e \in \{0,1\}, \forall_e \subset E \ (4)$$

Where x_e is the binary decision variable that connects the edge to the spanning tree. The variable c_e is given, as the associated cost, or in our example the length of the individual edge, whenever connecting the edge to the tree. The cost of connecting an edge is assigned whenever x_e takes the value of 1 as mentioned in constraint (4).

Constraint (2) ensures the right number of edges in the solution, where constraint (3) that there are no cycles or sub tours (Stougie & Canzar, 2011).

5.2.1.1. Algorithms to solve the minimum spanning tree

Commonly used algorithms in solve the spanning tree problem are Prim's- or Kruskal's algorithm. In contrast to prim's algorithm Kruskal's algorithm finds a minimum spanning forrest for each connected node in the spanning tree (Kruskal, 1956), which is a quite time consuming operation in problems where the number of nodes to be connected are large. Prim's algorithm on the other hand described by R.C. Prim (Prim, 1957), uses the following procedure, which is to be considered less time consuming, to solve a minimum spanning tree problem (Balakrishnan & Render, 2007).

1. Select any node in the network.

2. Connect this node to its nearest node.

3. Considering all the connected nodes, find the nearest *unconnected* node and then connect it. If there is a tie, and two or more unconnected nodes are equally near, select one arbitrarily. A tie suggests that there may be more than one optimal solution.

4. Repeat step 3 until all the nodes are connected.

Due to the conviction that Prim's algorithm finds a solution in less time, this algorithm is going to be used for solving the minimum spanning tree problem in this given context. For automating Prim's Algorithm the pseudo code for programming is given in Appendix 9.

5.2.1.2. Results when using Prim's Algorithm

Whenever using Prim's algorithm the nodes are connected in beeline as seen in Appendix 10, with a total distance of 128,1 km given by the sum of all the assigned distances between the power plants. This solution might course some real life problems due to restricted areas seen in Appendix 11, as well as the fact that the algorithm suggests to build the pipeline offshore. An offshore solution is considered more costly than building onshore, and therefore a penalty function or factor needs to be added to the Euclidian distance to correct this and to get a feasible optimal solution. Whenever building offshore or building in areas violating the plane surface the Euclidean geometry is violated, which will affect the final result (Coit & Smith, 1995).

5.2.1.2.1. Incorporating junctions and penalties

In some situations as mentioned it's not possible to connect the nodes in beeline due to constraints not include in the constraint list for the minimization problem. In such situations the model needs to be modified to provide the user with a usable and realistic solution for implementing. These modifications can be subject to:

- Preserved or protected areas (Forest, buildings, etc.)
- Areas with difficult construction conditions (Lakes, swamps, mountains, etc.)
- Local reluctance
- Other external conditions/factors

To be able to work things, so that these constraints are satisfied, junctions are introduced as shown in Appendix 12.

To show how a junction can be added into the model, the junction (Junction 1) at coordinate (-9, 16) is used for illustration. Building a pipeline under water can be rather costly as mentioned in 5.2.1.2. With this in mind, connecting Hvide Sande and Kloster, it might be desirable to stay on shore. The junction which in this situation is a Steiner point is placed strategically to minimize costs as shown in the very same appendix. A penalty factor is added to the distance matrix from Hvide Sande to Kloster, Ringkøbing and Lem, as described to make sure that the shortest distance chosen between the two locations is via the junction instead of going under water and thereby violating the Euclidean formula. Ringkøbing and Lem are added to make sure that the connection will never go across the lake in any circumstances.

Penalty factor added:

From	To
Hvide Sande	Kloster, Ringkøbing, Skjern, Lem

Table 5

Using these junctions and penalties to predefine parts the final solution, might lead to sub-optimality since the total length of the pipeline might be increased in contrast to adding a Steiner point, but at least these junctions will provide the user with a feasible solution. Dealing with this sub-optimality a Steiner algorithm may be able to find an even better feasible solution, starting from the best-known feasible solution adding Steiner points to the tree as seen in West African natural gas pipeline problem described by E.K. Donkoh, S.K. Amponsah and K.F. Darkwah (Donkoh, Amponsah, & Darkwah, 2011).

Appendix 13 shows the solution whenever building the pipeline around the lake instead of across. The total distance has thereby increased to 135,5 km compared to 128,2 km, which as mentioned is a consequence to predefining the solution.

5.2.2. Step 2 - Slurry Pipelines

The next step is to connect farms to the biogas plants, as described in 5.1.2., taking the individual biogas plant along with the attached cluster of farms, connecting them in a spanning tree, exactly as in Step 1 by using Prim's algorithm.

Appendix 14 shows such an example where the algorithm finds the minimum total length of the pipeline to be 5,48 km.

5.2.3. Step 3 - Connection Pipelines

When connecting the biogas plant to the main pipe, connecting points with a predefined interval are made on top of the same straight line that represents the main pipe as shown in Appendix 15. With these connection points in place Prims algorithm finds the shortest distance from the respective biogas plants to one of the defined connection points.

As mentioned in 5.1.2 this way of connecting might lead to sub-optimality, since the main pipe don't adapt to the connection of the biogas plant. To deal with this the connection point should be shifter as mentioned in the very same section.

In other words the connection point should be converted into a Steiner point that is shifted to minimizing the distance with respect to the power plants and the biogas plants shown in Appendix 1, in order to curve the main pipe line and thereby making it adapt.

6. General Applicability

The Ringkøbing-Skjern project has been monitored with deep interest from several other municipalities in Denmark. Among those are Horsens municipality together with Mariager Fjord & Vesthimmerland Municipality. Also outside of Denmark the project have attracted attention, especially in the Baltic Sea countries.

This attention comes because of the project mentality and the incentive in Ringkøbing-Skjern, along with the way that things are structured and carried out. The know-how, ideas, and experience gathered in this project can in some aspect be carried on to similar projects in the future, which will make it easier to get started due to a known framework.

7. Future research

As given in 5.1.1.3 it's not profitable to upgrade biogas into natural gas at the moment. However it's pointed out that economies of scale would affect the upgrading prices. Further research on how big an upgrading facility should be in order to be profitable and to compete against natural gas could therefore be decisive for other similar projects.

Since the Ringkøbing-Skjern Project still an ongoing project, locating additional biogas production facilities to make sure that all possible biogas reserves in the municipality is used may be subject to further research as well. Appendix 16 shows a pixel value map of the biomass reserves in Ringkøbing-Skjern municipality. A facility locating frameworks could be favourable in this context.

This rapport has as well been working with Euclidean distances, which has been violated in 5.2.1.2. To be able to make a complete cost calculation, the exact penalties of building in certain areas should be added to the Euclidean distances. An option could be the making of a similar pixel-map as seen in Appendix 16. Instead of biomass reserves the costs of building should be attached to the individual pixel thereby being able to make a cost matrix instead of a distance matrix, which would provide the model builder with an even better foundation for a usable final result for implementing.

From the delimitations it's given that this rapport does not focus on the dimensioning of the pipe. Gas flows together with slurry flows and pipeline capacities could be subject to further research as well as the CO^2 gain when pumping the slurry instead of transporting it by truck.

Bibliography

Balakrishnan, N., & Render, B. &. (2007). Chapter 5: Transportation, assignment, and network models. In *Managerial decision modeling with spreadsheets* (Vol. 2, pp. 185-224). Prentice Hall.

Birge, J. R., & Malyshko, V. (1985). Methols for a network design problem in solar power systems. *Comput. & Ops. Res. , 10* (12), 125-138.

Boruvka, O. (1926). *Contribution to the solution of a problem of economical construction of electrical networks.* Elektronický Obzor.

Coit, D. W., & Smith, A. E. (1995). *Penalty Functions.* University of Pittsburgh, Department of Industrial Engineering. Pittsburgh, Pennsylvania: A Joint Publication of Oxford University Press and Institute of Physics Publishing.

CProgramming.com. (n.d.). Retrieved September 16, 2011 from Minimum Spanning Tree: http://www.cprogramming.com/tutorial/computersciencetheory/mst.html

Energi styrelsen. (2010, May 11). Modelberegning for biogasforsyning af Skjern.

Donkoh, E. K., Amponsah, S. K., & Darkwah, K. F. (2011). Optimal Pipeline Connection for the West African Gas Pipeline Project. *Research Journal of Applied Sciences, Engineering and Technology , 3* (2), pp. 67-73.

Jørgensen, K. (2011). Barmarksvæker. Skejby, Denmark: Videncentret for Landbrug.

Jørgensen, K. (2011). Biogas omregner. Skejby, Denmark: Videncentret for Landbrug.

Jensen, T. K. (2009). *Biogas til nettet.* Dansk Gasteknisk Center a/s. Hørsholm: Dansk Gasteknisk Center a/s.

Jensen, T. K. (2011). *Establishment of a biogas grid and interaction between a biogas grid and a natural gas grid.* Dansk Gasteknisk Center a/s. Hørsholm: Dansk Gasteknisk Center a/s.

Kruskal, J. B. (1956). On the shortest spanning subtree of a graph and the traveling salesman problem. *Proc. Am. Math. Soc. , 7* (1), pp. 48-50.

Lund, H., Morthorst, P., Mathiesen, B. V., & Meyer, N. I. (2011). *CEESA.* Aalborg: Aarborg Univercity.

Miljøministeriet, Biogassekretariatet, Naturstyrrelsen Aarhus. (2011). 1-4_GIS1_RKSK. Aarhus, Denmark: Miljøministeriet.

Olesen, J. (2009). *Notat om biogaspotentiale i Ringkøbing-Skjern Kommune.* PlanEnergi.

Prim, R. C. (1957). Shortest connection networks and some generalizations. *Bell System Technical Journal , 36*, pp. 1389–1401.

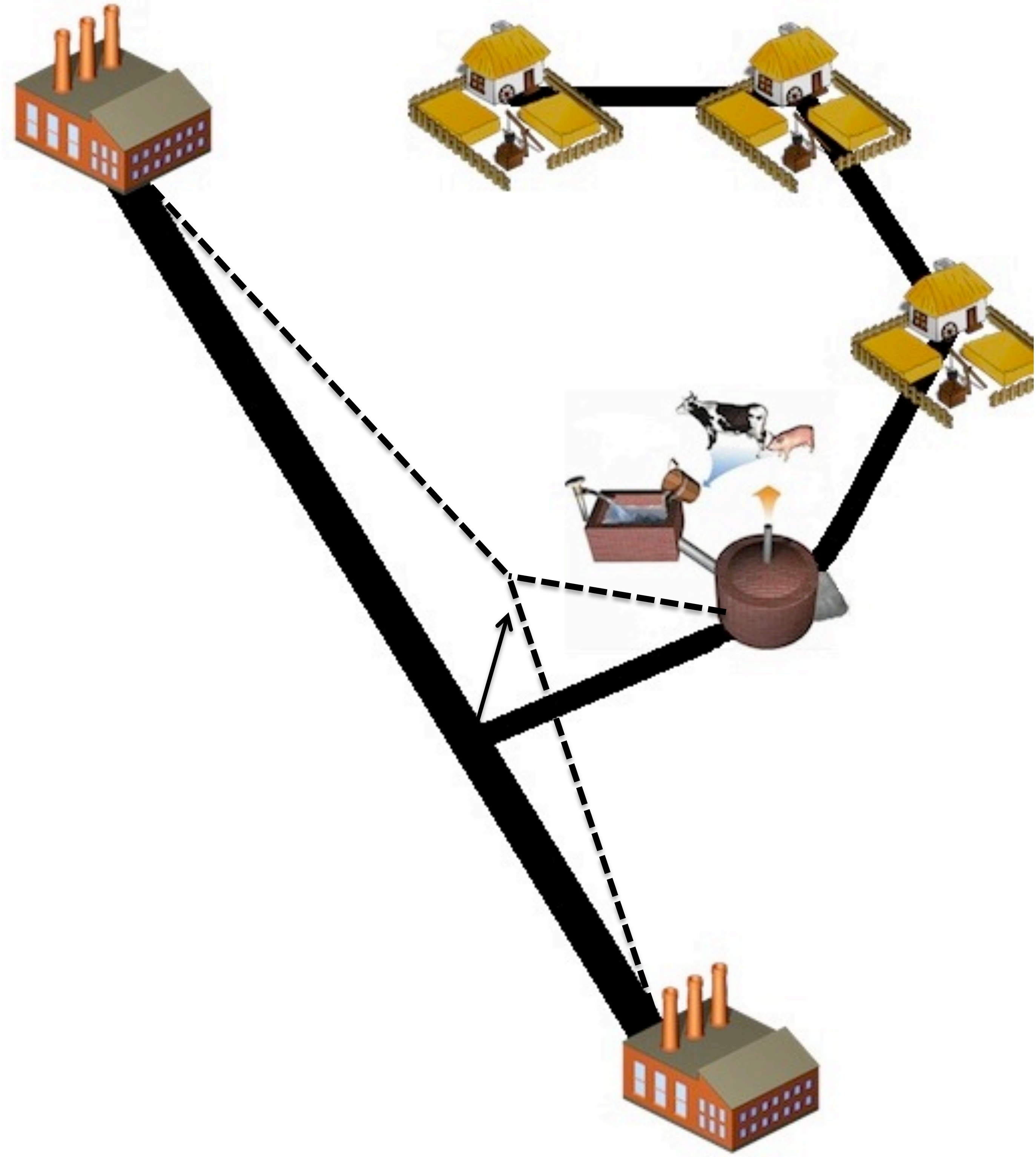
Skjern Fjernvarmecentral A.m.b.a. (2010). *Årsrapport.* Skjern: Skjern Fjernvarmecentral A.m.b.a.

Stougie, L., & Canzar, S. (2011). *Advanced Linear Programming.* Retrieved September 20, 2011 from Vrije Universiteit Amsterdam: personal.vu.nl/l.stougie/Courses/ALP/col10.pdf

Ringkøbing-Skjern Kommune. (2011). From Energi 2020: http://energi2020.dk.linux97.curanetserver.dk/

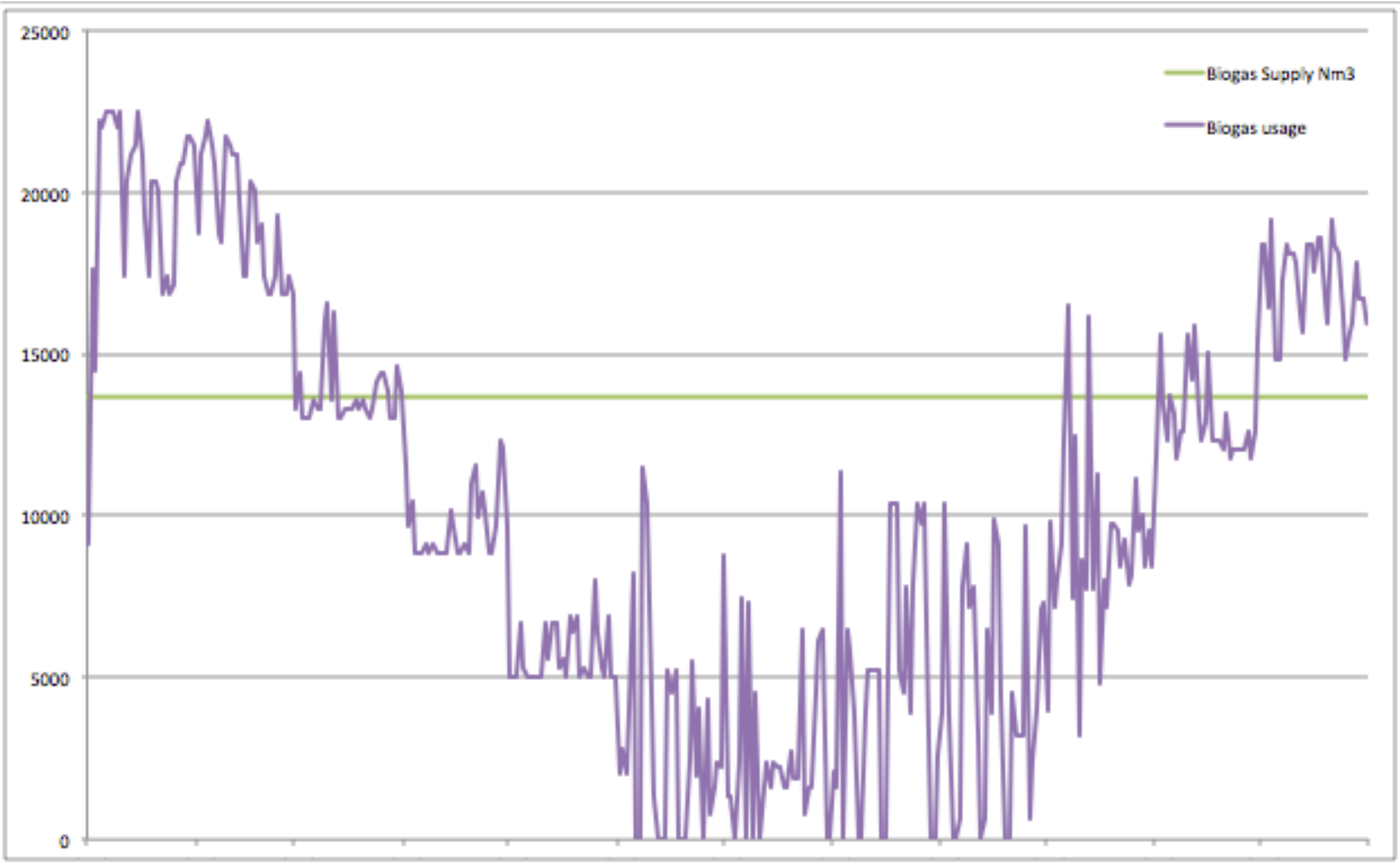
Appendix 1

Pipeline connection point shifting



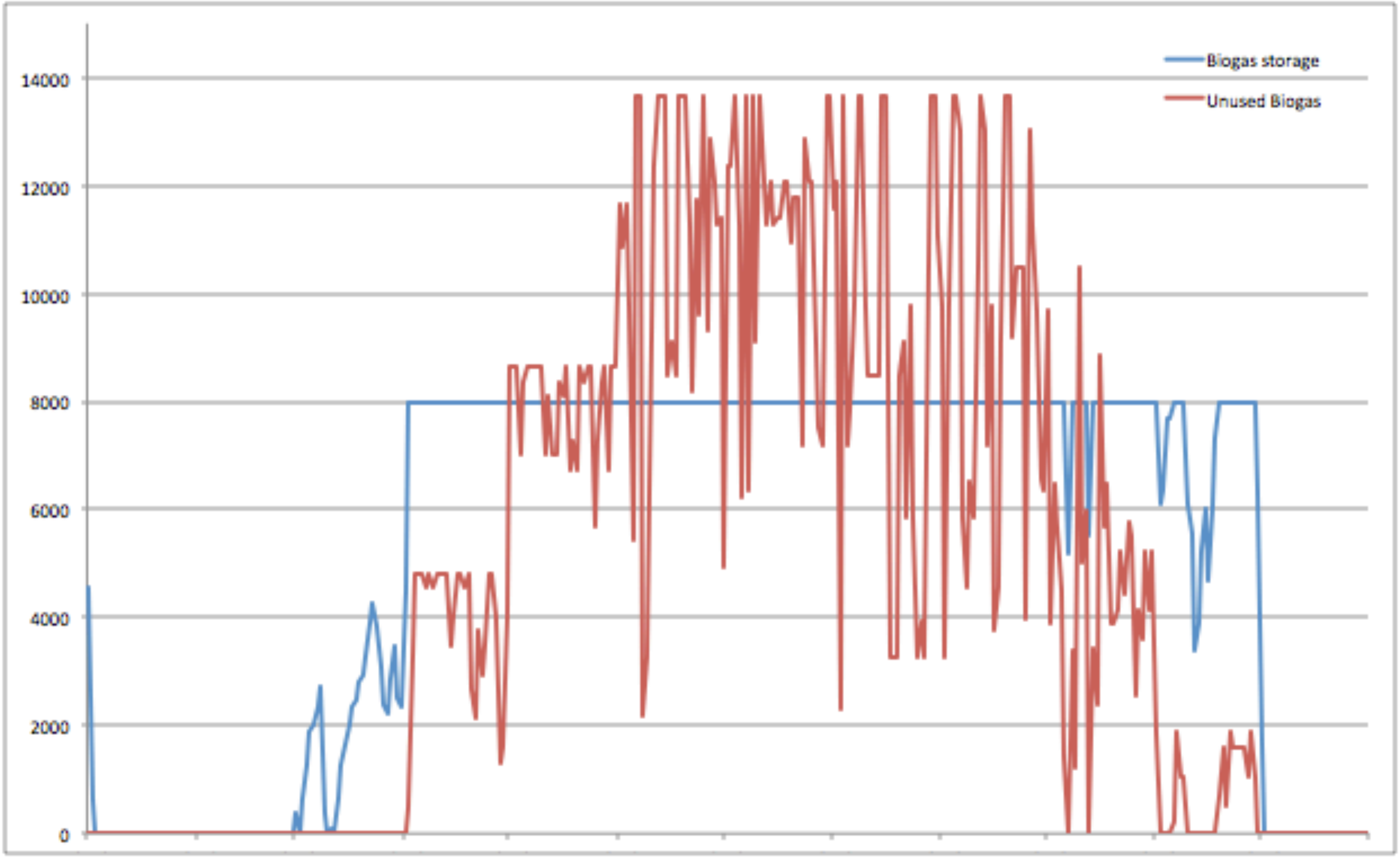
Appendix 2

Scenario 1 – Biogas output



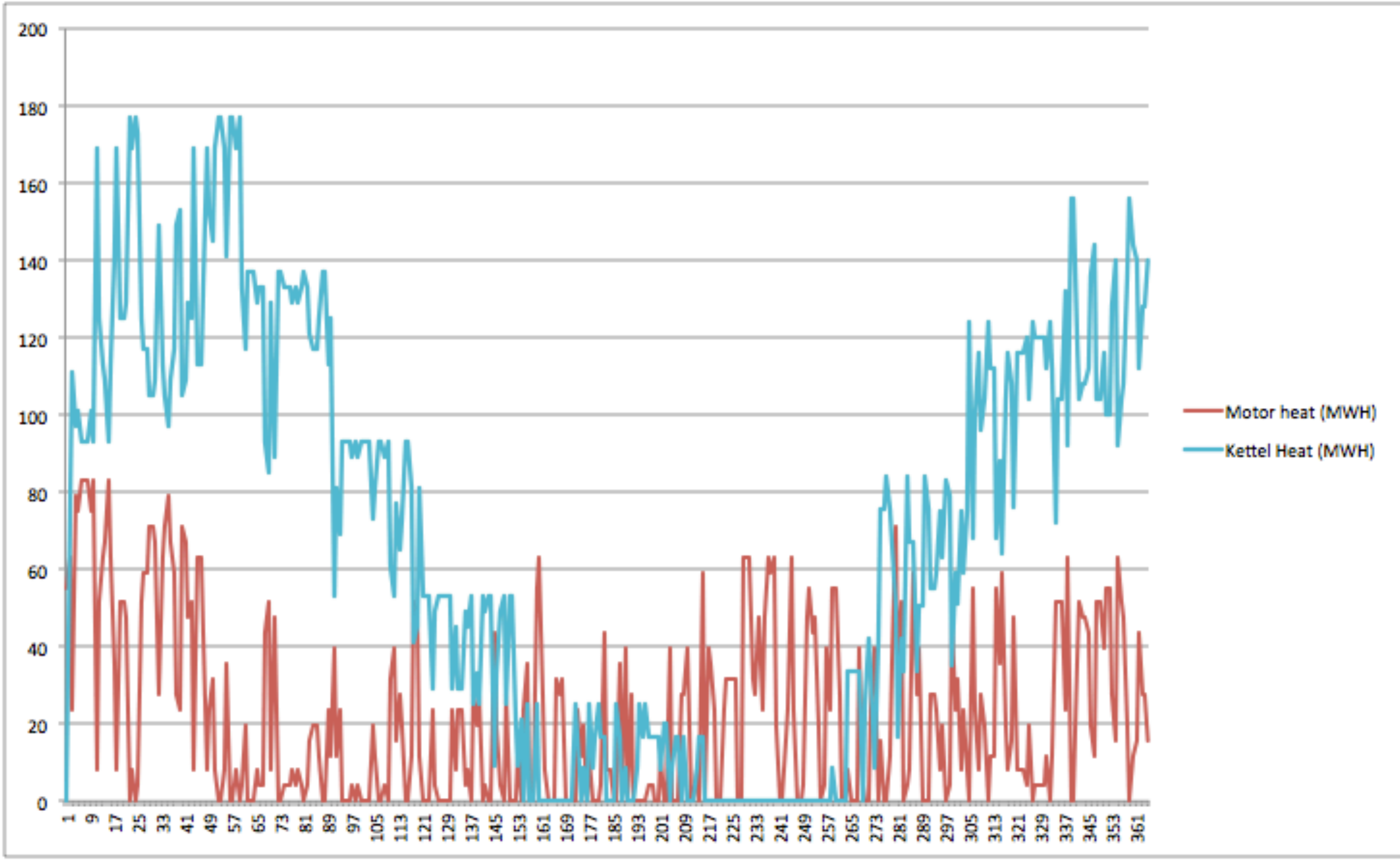
Appendix 3

Scenario 1 – Excess biogas output



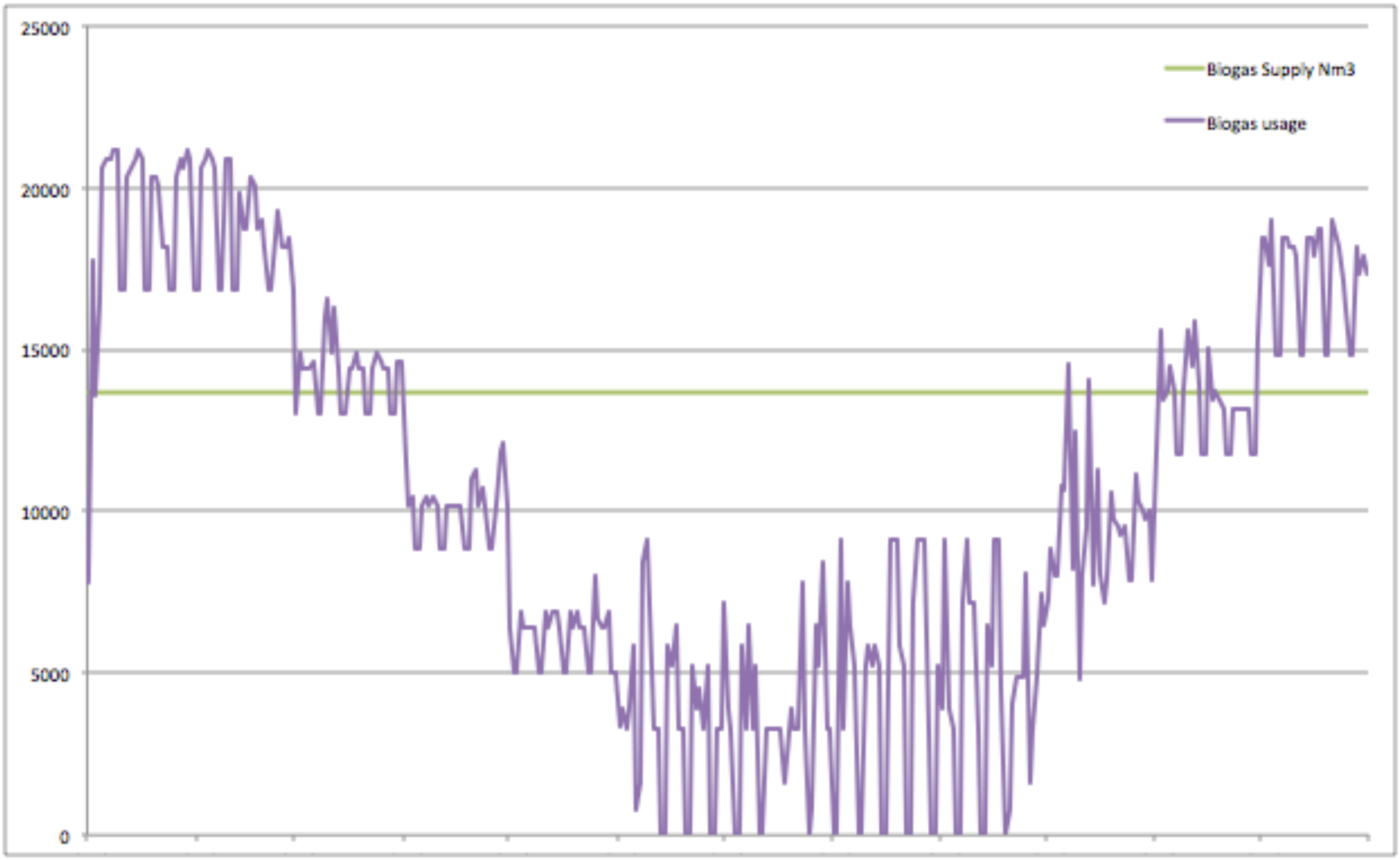
Appendix 4

Scenario 1 – Production output



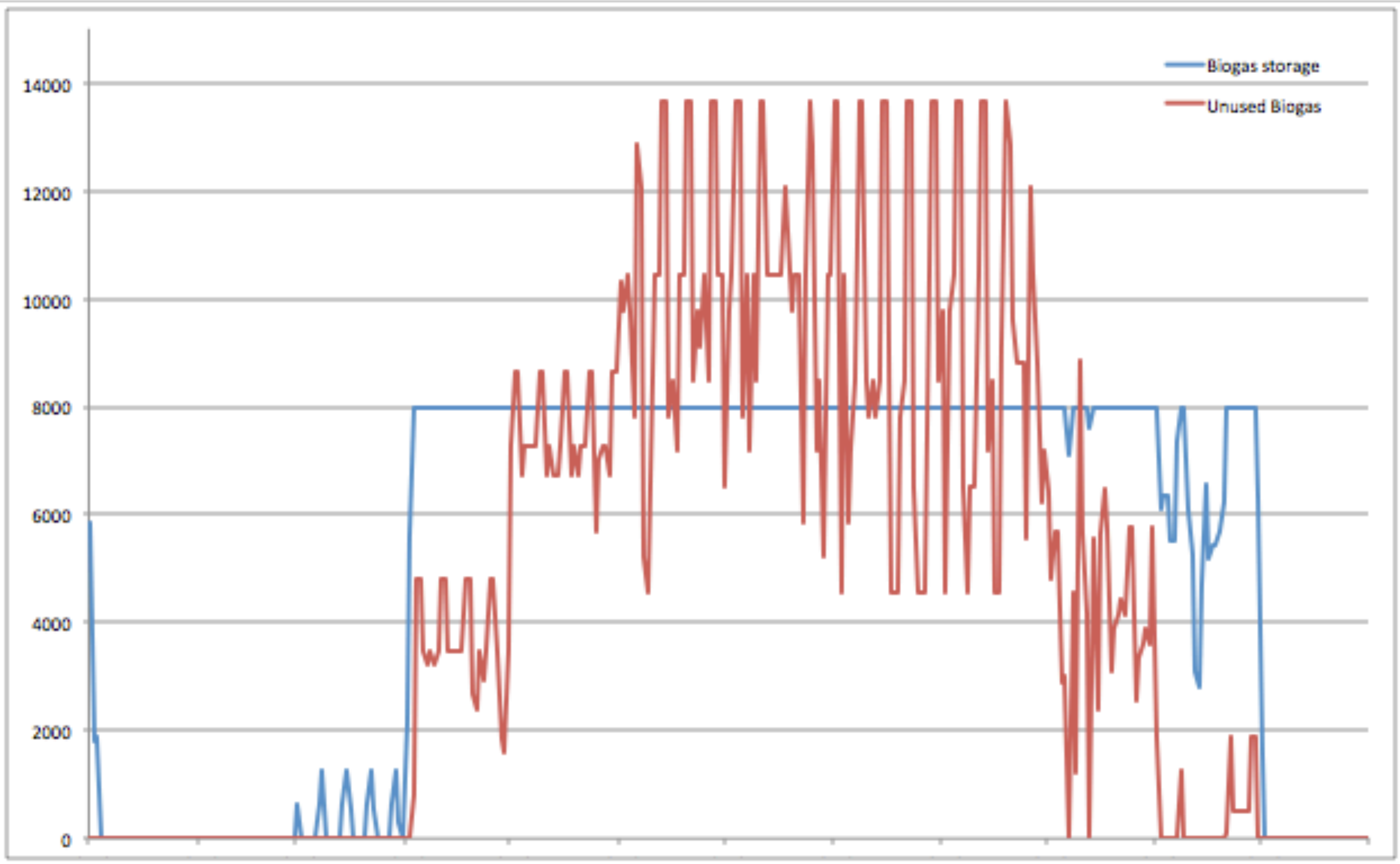
Appendix 5

Scenario 2 – Biogas output



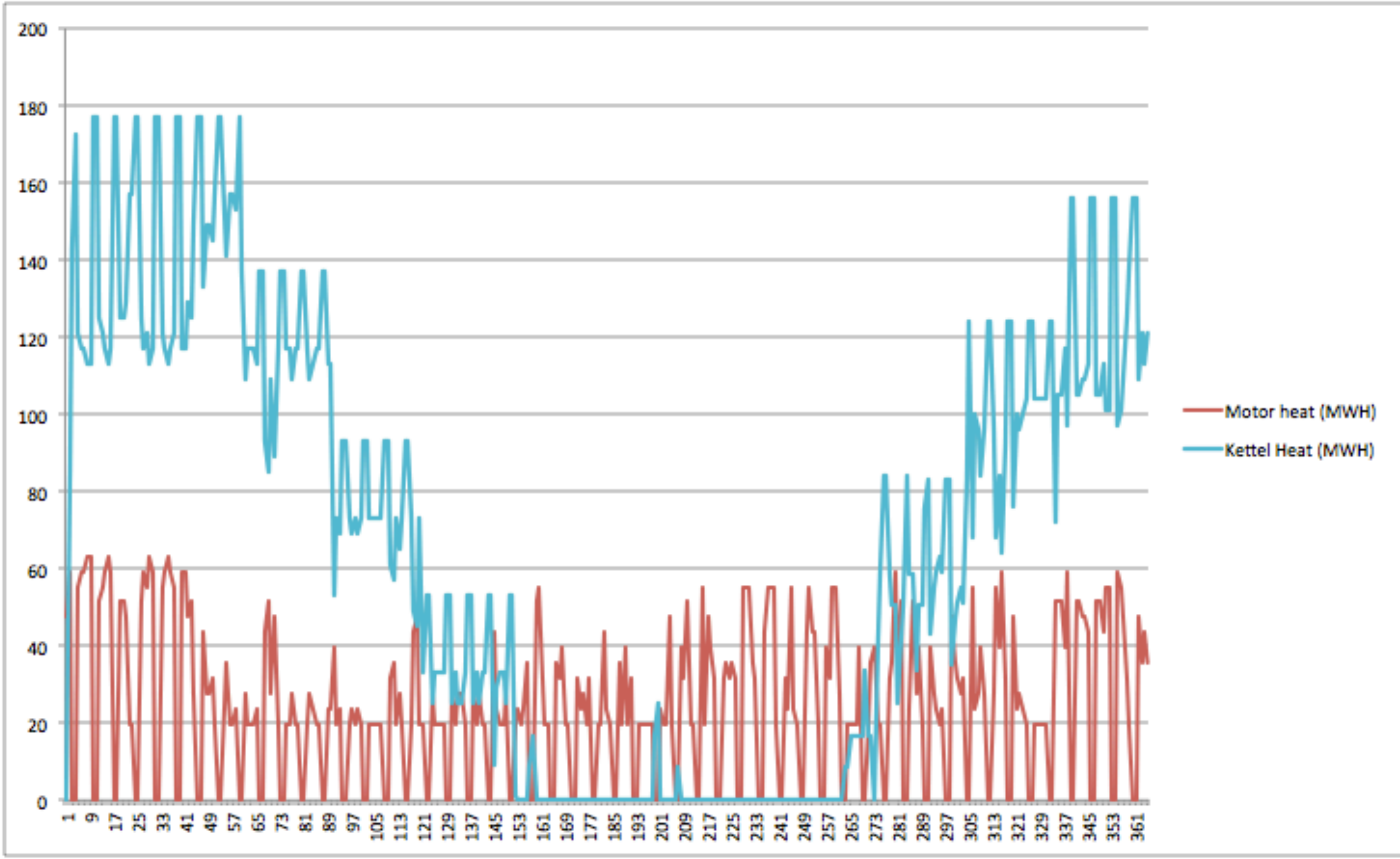
Appendix 6

Scenario 2 – Excess biogas output



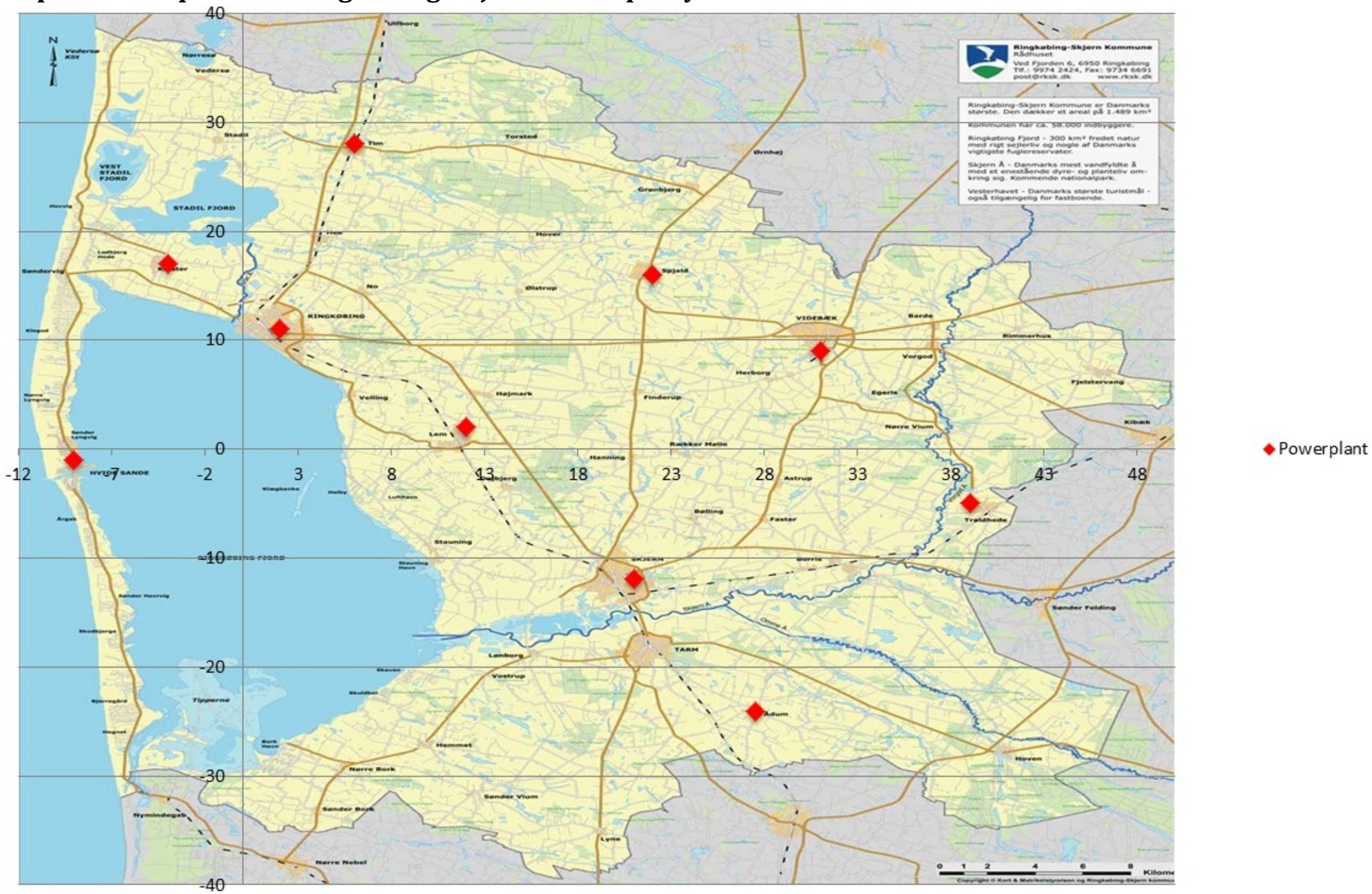
Appendix 7

Scenario 2 – Production output



Appendix 8

Map of Power plants in Ringkøbing-Skjern Municipality



Appendix 9

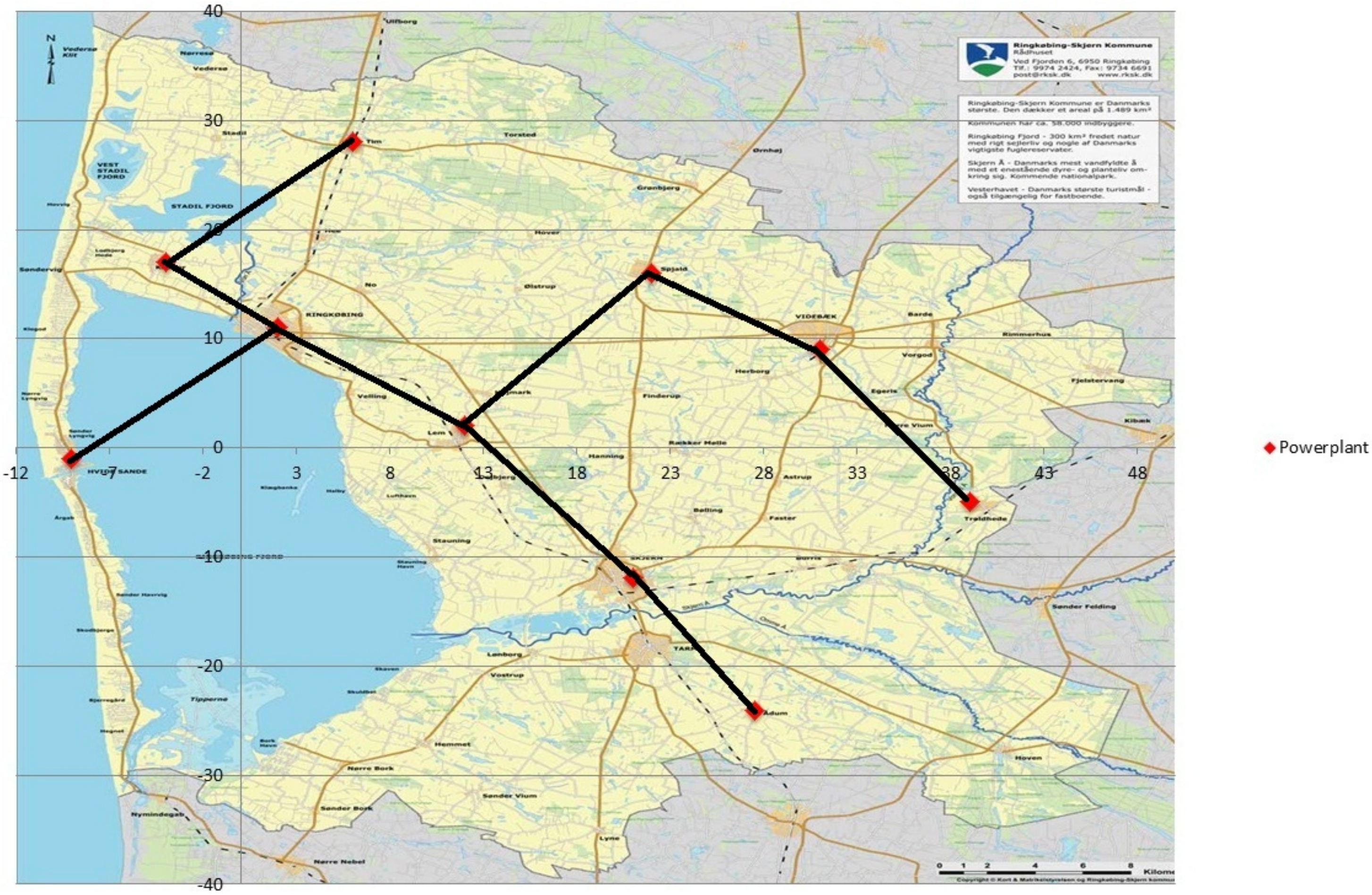
Pseudo code for Prim's Algorithm

```
Given a graph, G, with edges E of the form (v1, v2) and vertices V

dist : array of distances from the source to each vertex
edges: array indicating, for a given vertex, which vertex in the tree it
       is closest to
i     : loop index
F     : list of finished vertices
U     : list or heap unfinished vertices

/* Initialization: set every distance to INFINITY until we discover a way to
link a vertex to the spanning tree */
for i = 0 to |V| - 1
    dist[i] = INFINITY
    edge[i] = NULL
end

pick a vertex, s, to be the seed for the minimum spanning tree

/* Since no edge is needed to add s to the minimum spanning tree, its distance
from the tree is 0 */
dist[s] = 0


while(F is missing a vertex)
   pick the vertex, v, in U with the shortest edge to the group of vertices in
       the spanning tree add v to F

   /* this loop looks through every neighbor of v and checks to see if that
    * neighbor could reach the minimum spanning tree more cheaply through v
    * than by linking through a previous vertex */
   for each edge of v, (v1, v2)
        if(length(v1, v2) < dist[v2])
            dist[v2] = length(v1, v2)
            edges[v2] = v1
            possibly update U, depending on implementation
        end if
    end for
end while
```

Source: (CProgramming.com)

Appendix 10

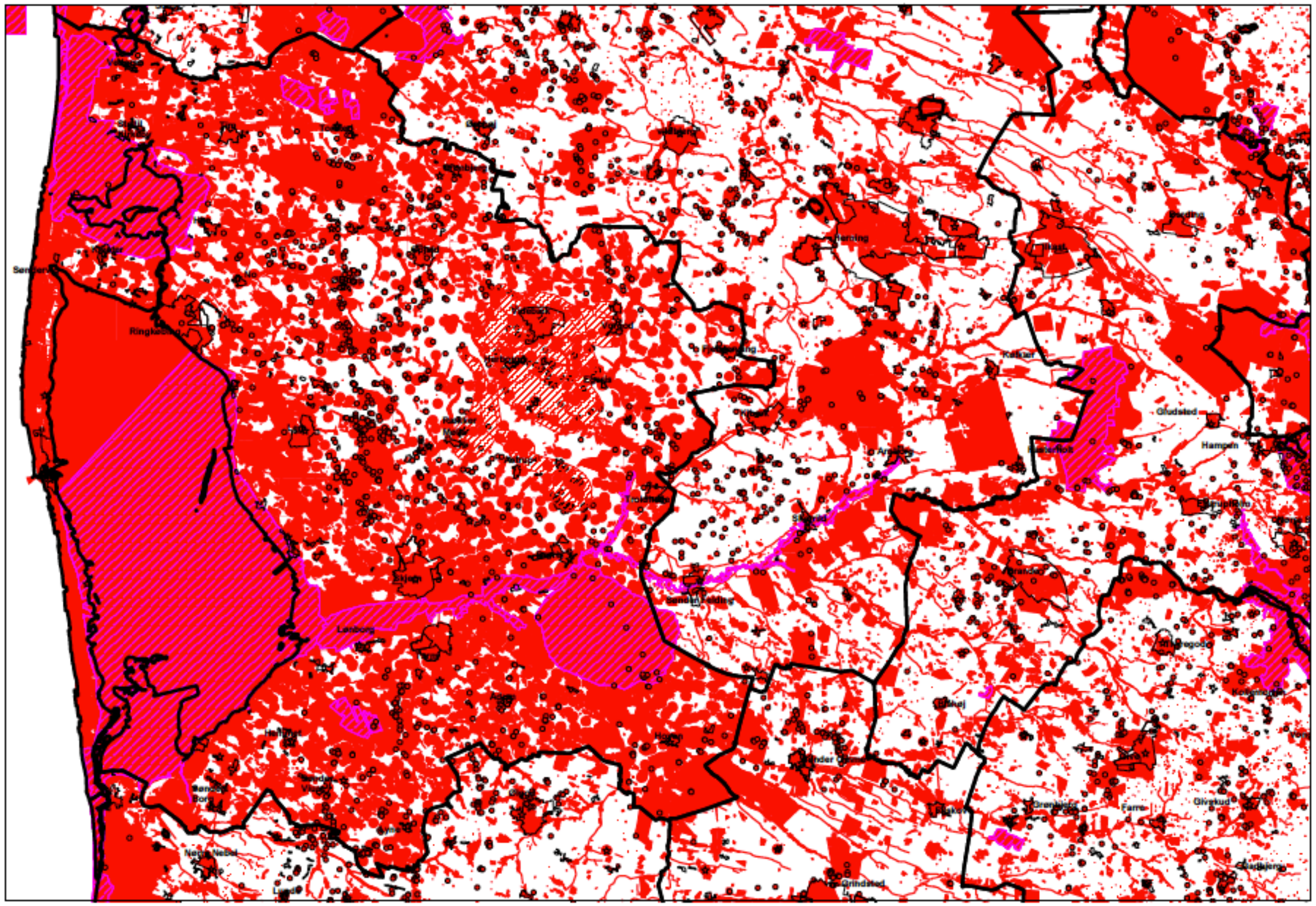
Main Pipeline - Prim's Algorithm



Minimum Spanning Tree		
From	**To**	**Distance**
Starting node	Hvide Sande	0
Hvide Sande	Ringkøbing	16,2788206
Ringkøbing	Kloster	8,485281374
Ringkøbing	Lem	13,45362405
Kloster	Tim	14,86606875
Lem	Skjern	16,64331698
Skjern	Ådum	13,64734406
Lem	Spjald	17,20465053
Spjald	Videbæk	11,40175425
Videbæk	Troldhede	16,1245155

Appendix 11

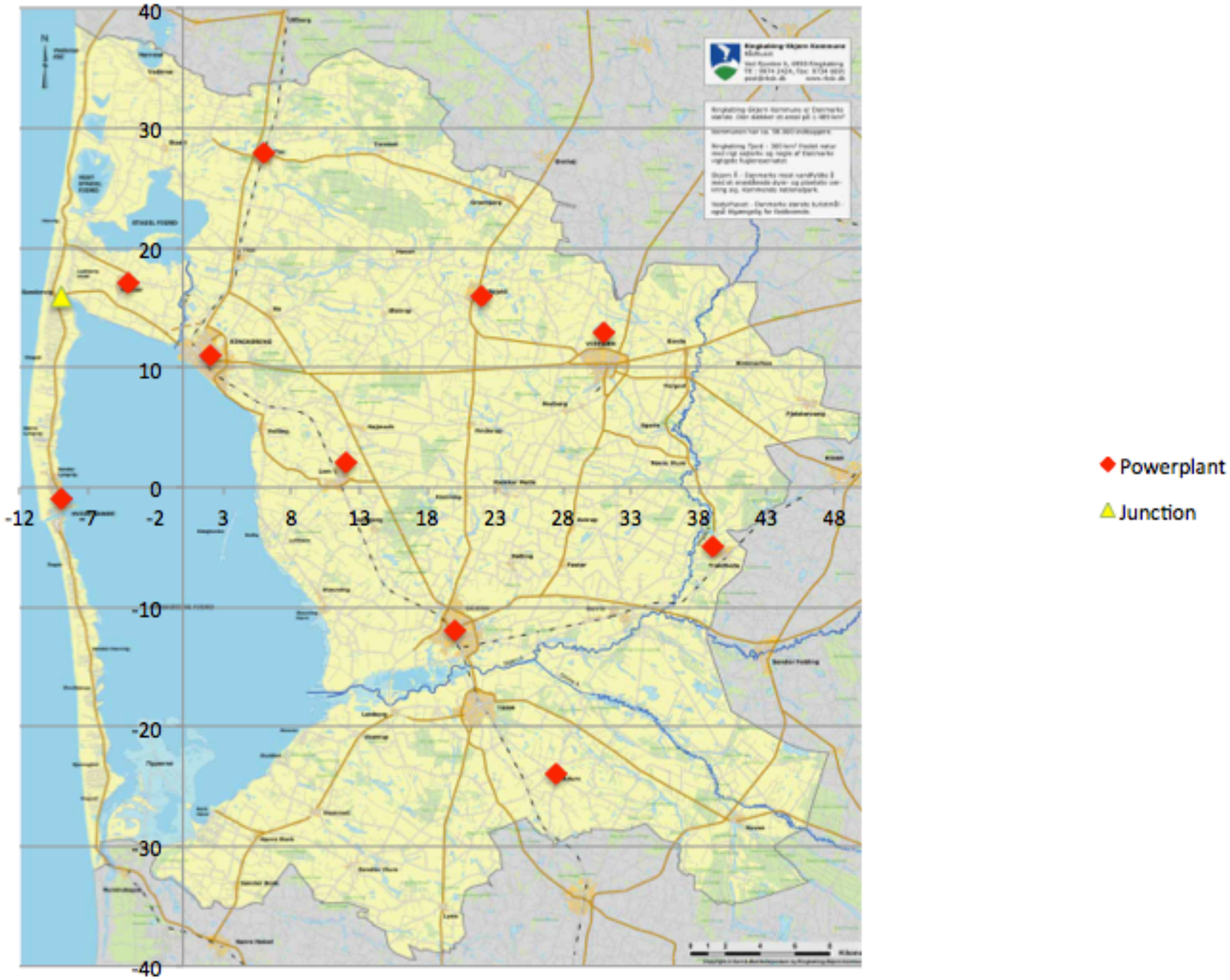
Restrictive zones in Ringkøbing-Skjern Municipality



Source: (Miljøministeriet, Biogassekretariatet, Naturstyrrelsen Aarhus, 2011)

Appendix 12

Incorporating junctions



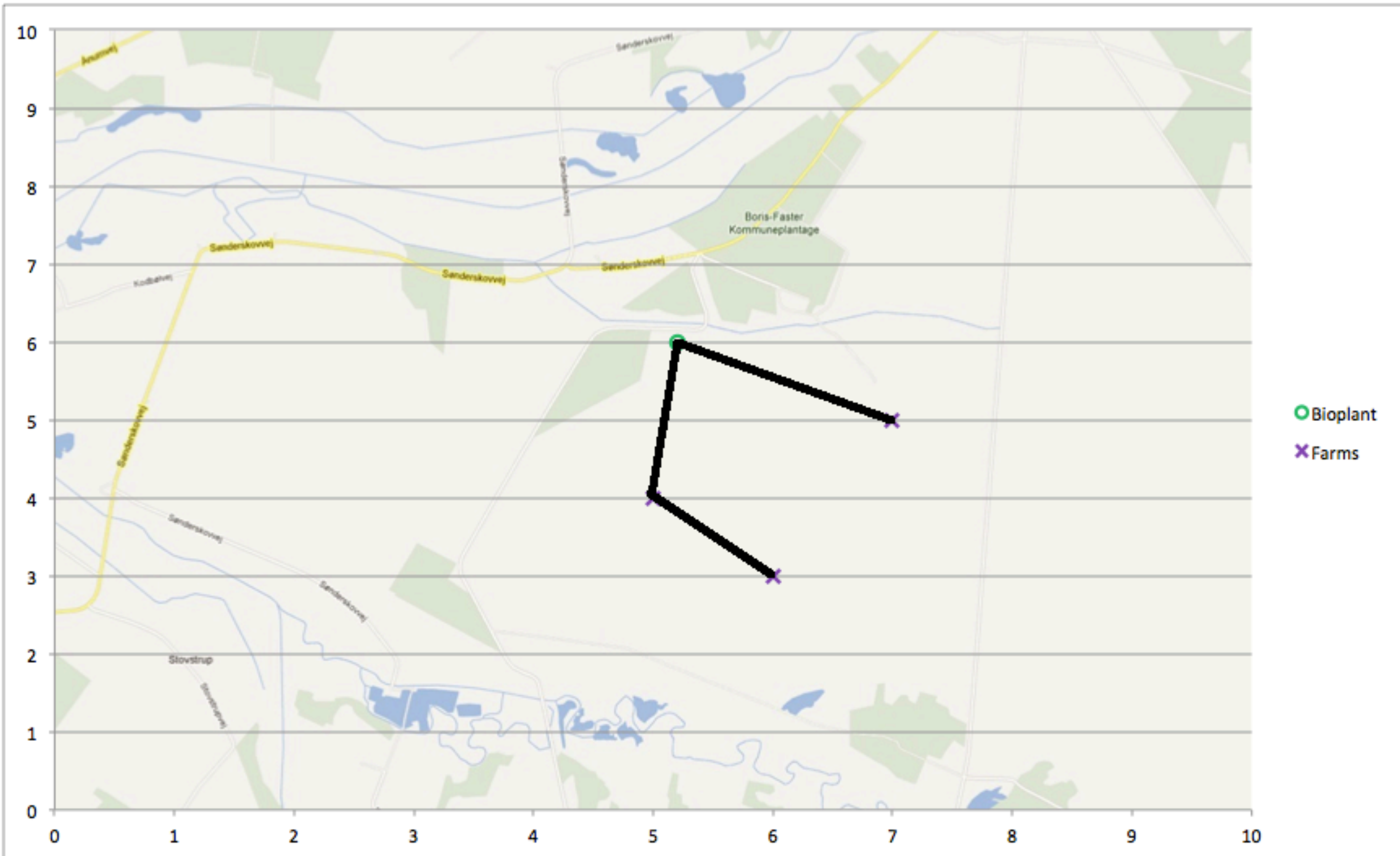
Appendix 13

Main pipeline – Prim's algorithm with junctions and penalty factors

Minimum Spanning Tree		
From	**To**	**Distance**
Starting node	Hvide Sande	0
Hvide Sande	Junction 1	17
Junction 1	Kloster	5,099019514
Kloster	Ringkøbing	8,485281374
Ringkøbing	Lem	13,45362405
Kloster	Tim	14,86606875
Lem	Skjern	16,1245155
Skjern	Ådum	14,1509717
Lem	Spjald	17,20465053
Spjald	Videbæk	9,486832981
Videbæk	Troldhede	19,6977156

Appendix 14

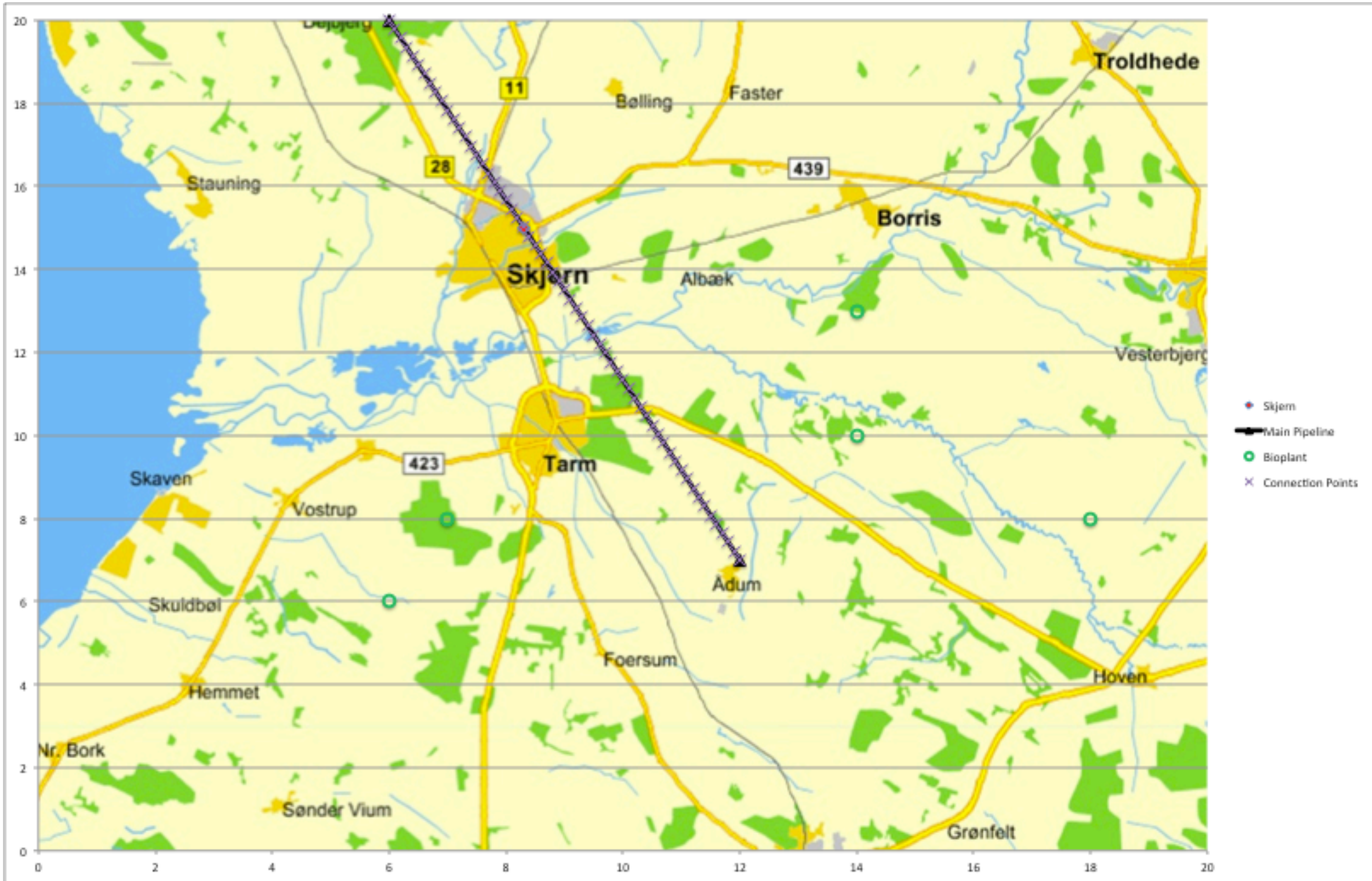
Connecting a Biogas plant with the farm cluster



Minimum Spanning Tree		
From	**To**	**Distance**
Bioplant 4	Farm 1	2,009975125
Farm 1	Farm 2	1,414213562
Bioplant 4	Farm 3	2,059125987

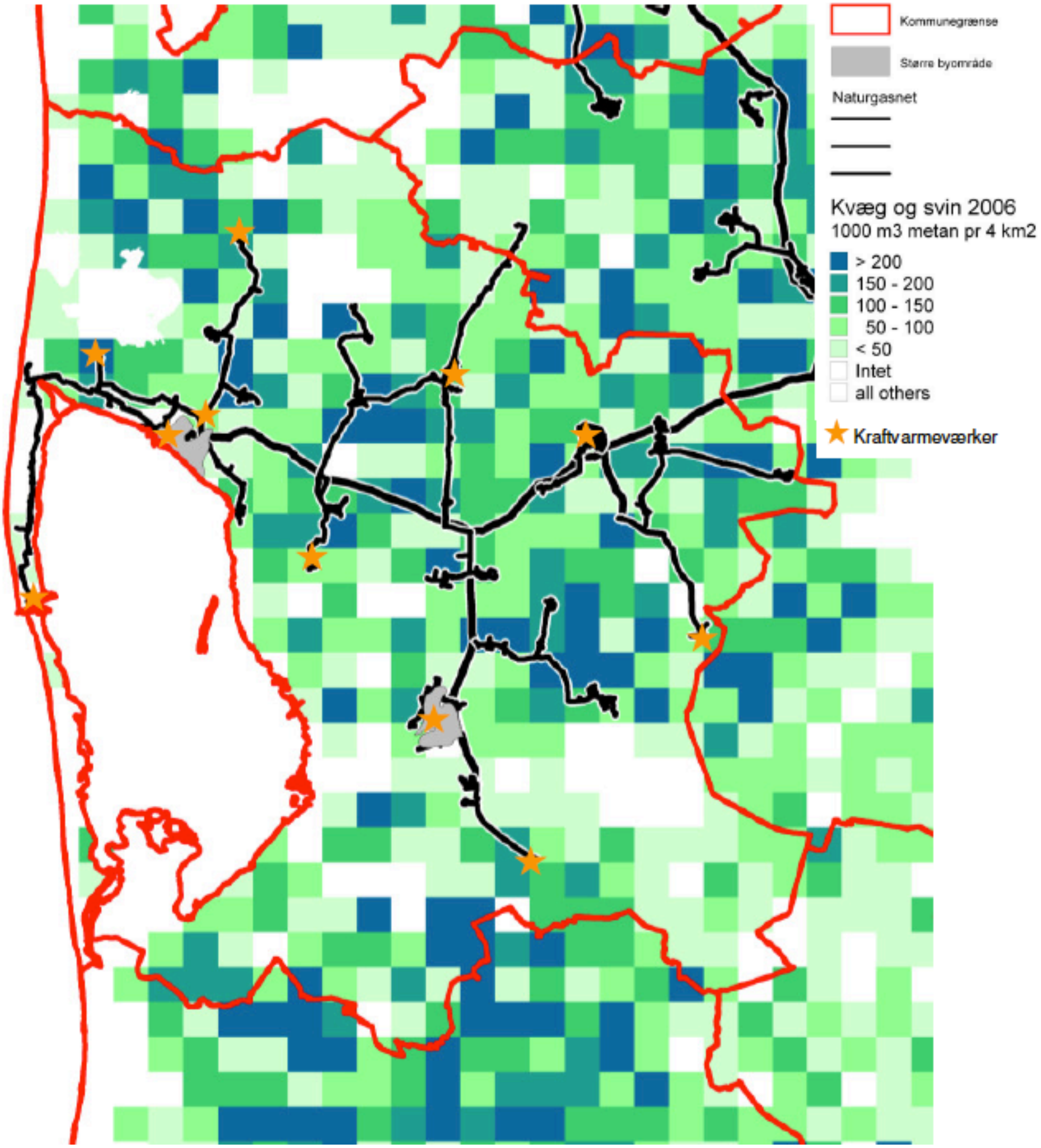
Appendix 15

Connecting biogas plants to the main pipe



Appendix 16

Biomass reserves in Ringkøbing-Skjern municipality



Source: (Olesen, 2009)