# Final Report over the EUDP project:

# "Demonstration of the AD-Booster system for enhanced biogas production"

**Partners: BioVantage.dk Aps, Ribe Biogas A/S, AAU and Sweco.**

*October 7, 2017.*

# Final report

## 1.1 Project details

| | |
|---|---|
| **Project title** | Demonstration of the AD Booster system for enhanced biogas production |
| **Project identification (program abbrev. and file)** | J.nr. 64015-0029 |
| **Name of the programme which has funded the project** | EUDP |
| **Project managing company/institution (name and address)** | BioVantage.dk ApS |
| **Project partners** | Grontmij A/S (Sweco), Ribe Biogas A/S, Aalborg Universitet |
| **CVR** (central business register) | 36498544 |
| **Date for submission** | October 13, 2017 |

## 1.2 Short description of project objective and results

English version

The aim of the project was to conduct a commercial-scale testing of the AD-Booster process to verify enhanced biogas production previously obtained in laboratory and pilot scale in realistic scale. For this purpose, we constructed and implemented a 2 ton/hour AD-Booster plant at Ribe Biogas. Through side-by-side operations of full-scale secondary biogas reactors at Ribe Biogas with and without the AD-Booster process incorporated, we were able to show ca. 3 times higher methane production in the reactors receiving materials from the AD-Booster compared to reactors receiving the same material but without any prior treatment. From the methane production at Ribe Biogas, it was further possible to determine that the methane yield of manure fibre increases 2.5 times after AD-Booster treatment from ca. 90 m3/ton VS to ca. 220 m3/ton VS. The AD-Booster plant at Ribe Biogas was found to be capable of constant operation over extended periods without major down-periods and with slightly increasing results due to optimization along the way. This clearly shows that the technology has a high degree of maturation and is ready for future large-scale implementation. The positive outcome of the tests has led to commercial activities and a 12 ton/hour AD-Booster system is now under detailed planning with a construction and start-up date in 2018. The technology will allow biogas plants to operate economically on manure, deep litter and agricultural residues without the need for addition of organic industrial waste or energy crops. This result supports the Danish development towards a fossil-free energy sector and is expected to ultimately lead to expansion of the biogas sector in the future.

Dansk version
Formålet med projektet var at gennemføre en fuldskala test af AD-Booster processen for at verificere de resultater, som var opnået tidligere i laboratoriet og ved pilotforsøg, men nu i fuld skala. Til dette formål blev en 2 ton/time AD-Booster konstrueret ved Ribe Biogasanlæg. Igennem forsøg med forskellige reaktorer, som var direkte sammenlignelige, opnåede vi ca. 3 gange højere gasproduktion i de reaktorer, som modtog materiale, som havde været igennem AD-Booster processen sammenlignet med den reaktor, som fik det samme- men ikke AD-Booster behandlede- materiale. Fra den målte methan produktion i reaktorerne var det muligt at vise, at methan udbyttet fra gyllefibre stiger 2.5 gang efter behandling i AD-Boosteren fra ca. 90 m3/ton VS til ca. 220 m3/ton VS. AD-Booster anlægget på Ribe Biogas kunne opereres konstant over lange perioder uden længere stop og med svagt stigende udbytte, som følge af en løbende optimering. Resultaterne viser klart at teknologien har en høj modningsgrad, og er rede til fremtidig udbredelse i større skala. Den positive demonstration har medført kommerciel interesse for AD-Boosteren, og et 12 ton/time AD-Booster system er nu under detaljeret planlægning med en konstruktions- og start-up dato i 2018. Den nye teknologi gør det muligt for biogasanlæg at have en økonomisk drift kun ved brug af gylle, dybstrøelse og andre fibre såsom græs og halm og uden tilsætning af organiske affaldsprodukter og energiafgrøder som energimajs. AD-Boosteren understøtter direkte udviklingen imod udfasning af fossile brændstoffer i den Danske energisektor, og forventes i fremtiden at bidrage til væksten i biogassektoren.

### 1.3 Executive summary

The main objective of this project was to demonstrate the performance of the AD-Booster process at commercial-scale at an operating biogas plant. The operation of the AD-Booster at Ribe Biogas proved that the technology substantially increases the production of methane from anaerobic digestion. The patented wet oxidation/steam explosion process increased the conversion of digested manure fibers ca. 2.5 times, as expected from the previous pilot testing. The high efficiency of the AD-Booster treatment system was further verified by bench scale studies carried out in parallel to the test operation at Ribe Biogas.

In the AD-Booster, fibres, which are normally indigestible for the biogas process, are made available to microbes leading to a higher and faster convertibility of fibrous biomass to biogas. This effect allowed Ribe Biogas to shift from more costly high-yielding industrial wastes and energy-crops to using low-cost co-substrates such as deep-litter. This is an additional economic bonus of the AD-Booster besides the production of extra biogas.

After 5 month of initial operation, the AD-Booster was set-up for an extended test period where it was operated continuously for 7 months. During this test period, the operation of the AD-Booster was mainly done remotely along with 2 to 3 days of visit a week for adjustments or minor maintenance. The successful technical implementation of the system at Ribe Biogas demonstrated the technical applicability of the process at commercial-scale.

The long-term data obtained in the test period shows that the AD-Booster technology delivers the increase in gas production as predicted. These results correspond to an attractive Internal

Revenue of Return of implementing an AD-Booster at existing or new biogas plants, which has led to commercial interest from several biogas plant owners. An expanded AD-Booster system with a capacity matching a large full-scale biogas plants has been discussed with a specific biogas plant owner during the last month and a new construction is planned for 2018. After this much larger plant will be in operation, the technology will be ready for widespread penetration of the biogas marked.

The AD-Booster technology supports Danish and European energy policies and has the potential to strengthen and extend sustainable bioenergy production from residual biomass, thus contributes to the reduction of greenhouse gas emissions and fossil fuel dependency. In the future, the technology is expected to allow for far more widespread biogas expansion throughout Denmark and Europe.

### 1.4 Project objectives

The primary objective of the project was to verify the effect of the AD-Booster technology and to de-risk expansion and scale-up of the AD-Booster technology through a commercial small-scale demonstration. Overall, the idea was to confirm the enhanced biogas production observed in laboratory and pilot scale studies, and further to provide the necessary input on capital and operating costs before starting-up sale of the technology on the market. For this objective, we constructed a demonstration-scale AD-Booster system at Ribe biogas plant, which has been in full operation from the early fall of 2016 and forward. The realization of the project entailed several successive sub-objectives, which are divided into the project's milestones 1-4. These include detailed technical design and specifications (Milestone 1), Commissioning and testing (Milestone 2), System start up (Milestone 3) and Implementation of the test program (Milestone 4).

In the following, we provide a description of the project objectives and their related implementation steps. The project start-up date was July 1, 2015 and end-date was September 30, 2017.Originally, the project was intended to run until the end of 2017, but it was obvious from the beginning of 2017 that all objectives could be reached 3 month before this deadline leading to a change of the end-date.  Annex 1 provides an overview of the main work packages and their related tasks. Further, a Gantt diagram illustrating the actual execution of the project compared to the original schedule (Annex 2).

**System design and project planning (Milestone 1)**

In the first phase of the project (July to December 2015), the conceptual design of the AD-booster system was created. Biovantage (BV) led the conceptual design effort supported by Grontmij (GM) (GM was later taken over by Sweco). Detailed system design was done after this phase in a collaboration between BV and Haarslev Industries (HI), who calculated and drew all the technical parts derived from this design effort and further made the last detailed drawings of the final AD-Booster with all BV's modifications. RB and Sweco specified building-related modifications to enable the installation of the AD-booster at Ribe Biogas. As the plant was installed on a 1st floor concrete level in Ribe's new biomass storage building, reinforcement of the structure was found necessary for carrying the AD-Booster system. This meant that the AD-Booster had to be carried by steel reinforcement from the ground floor holding up the plant, which demanded that all parts had to be precisely fitted and set on very specific spots. BV did further work with Aalborg University (AAU) on a plan for verifying the data to be obtained during operation of the AD-Booster plant.

The AD-booster system was dimensioned to have a treatment capacity of 2 ton/hour dewatered fiber fraction derived after separation of the digestate from the primary digester (Reactor 4) found at Ribe Biogas (see figure 1). The overall operation of the separator was based on preliminary full-scale separation trials done at Ribe Biogas over extended time before purchasing of the final screw press system. The design was finalized and approved by BV in the beginning of October 2015 in accordance with the schedule in the original proposal.

After installation of the overall system at Ribe Biogas a number of corrections were made to the AD-Booster system to ensure proper operation of the plant. These changes involved a number of changes to the integration point between the AD-Booster and Ribe Biogas plant. A detailed operational plan was further defined by BV to ensure that the AD-Booster would be ready for an extended constant test period. This included definition of operational schedules, mass flows, optimal treatment temperature and pressure, maximizing of energy recovery within the system to bring down the internal use of biogas for steam production. Further, BV and AAU defined a documentation program for the test phase, describing sampling procedures and schedules, laboratory analysis and documentation. The operational and experimental planning provided a solid basis for the successful conduction of the test phase. In the course of the project, the test program had to be revised and laboratory procedures had to be adjusted along the way, to reflect the actual development of the project (see Implementation of the test program).

**Commissioning and testing (Milestone 2)**

The reinforcement of the building structure was carried out from December 2015 to March 2016, and the assembling of the AD-Booster plant was started just after the construction was finished. The major elements of the AD-Booster were comprised of a pre-heating system, a reactor with an in-feeding system, high pressure and low pressure flash tanks and tanks for holding the liquid fraction and the fibres. All these parts were further delivered by HI. The remaining elements were procured by Sweco A/S in accordance to the specifications defined by BV and HI. These were in particular the screw press for biomass dewatering, a steam generator, an oxygen generator, as well as various valves and instruments. Besides these elements, Sweco insured the contracts for the electrical installations, plumbing and piping using contractors, who previously had been working at Ribe Biogas, and were known to provide high quality installations.

The full assembly of the AD- Booster was delayed for around 3 months due to prolonged delivery times for central elements provided by HI. Due to limited space in the demonstration hall, the different installers were not able to work simultaneously, which further delayed the completion of the total installation by additional 3-4 weeks. In Maj 2016, the AD-Booster was ready for preliminary testing. During a period of 3 weeks, all elements and controllers were tested in a dry-test. These tests were carried out parallel to the final installation work, thereby partly recovering the delayed time and bringing the project back on schedule.  In the beginning of June 2016, we successfully conducted a wet test. Shortly after, the system was put into automated operation, running on approximately one third of the expected capacity.

The initial testing revealed the necessity for several minor modifications. These included the adjustment of the steam generator and the oxygen generator, an additional pressure relief unit for in-feeding in the system as well as the installation of a condensate separator in the steam system. These modifications were completed by end-June 2016. Thereafter, the AD-Booster has been in operations in full capacity with less and less staffing until 2017, where the plant has been operated un-manned for most of the time.

**Completion of start-up (Milestone 3)**

The AD-Booster was put into continuous operation shortly after the final tests had been completed. In the first weeks of operation, all operational procedures were thoroughly tested and the AD-Booster was only in operation during the daytime working hours, where the plant was staffed by one to two persons. By the end of June, the AD-Booster was operating from 8 am to 6 pm on all weekdays. Despite of the limited operation time, we could already observe a significant increase in the total biogas production at Ribe Biogas. During this time the AD-Booster delivered its treated material directly back in the primary biogas reactor (R4) resulting in a longer retention time for this material compared to the later set-up, where the material was added to the secondary reactors as outlined in Figure 1.

Already during start-up, we found that the steam generator had insufficient capacity, and was setting a limit to the amount of material, which we could treat. A modification of the generator unit was necessary to enable the operation of the AD-Booster at full capacity, which was accomplished in July 2016. Besides some additional minor adjustments, the complete system now proved to be operational and down-periods were getting fewer and fewer. In the following months, the AD-Booster operated continuously and the control system was changed to allow for remote operations. This online monitoring system with alarm functions enabled BV to carry out remote adjustments to all the major functions of the AD-Booster. The continuous operation revealed the need for the establishment of a stock of selected spare parts, as some specific elements were subjected to wear and tear and will have to be replaced on a regular basis. Parts to the AD-Booster is not standard parts will often be in back-order. These replacements constituted minor maintenance works, which mostly could be completed within 1 hour so keeping a stock will eliminate these types of problems. Overall, maintenance and repair did not affect the overall output of the AD-booster significantly.

**Implementation of the test program (Milestone 4)**

After the primary test period in the autumn of 2016, the AD–Booster was in full operation with full-time staffing at Ribe Biogas and showed consistent increased biogas yield when material was returned to the primary reactor R4 (8000 m3), which at that point was used as the destination for material from the AD-Booster. The final integration of the system between the primary and secondary biogas reactors was started in the end of 2016 after installation of new high-end methane meters in the three secondary biogas reactors R1, R2 and R3 (1650 m3 each). Now 2/3 of the material out of R4 was separated and the liquid was stored while the fibers (30% TS) were treated in the AD-Booster and afterwards fed to the two secondary reactors R1 and R2 along with the stored liquid- while 1/3 was fed directly from R4 to the last secondary reactor R3. This way we had a total parallel situation where R1 and R2 were test reactors and R3 was a control. In the beginning of the test period we had problems with the gas meters and it was finally found that they had been installed incorrectly by the company. After the methane meters were reinstalled in another position in the reactors, we were finally able to make correct measurements of the methane production in the parallel reactors. Before this, we further found that it was necessary to provide slight cooling of the material from the AD-Booster using a heat exchanger before it was fed into R1 and R2. This was necessary as this material now was supplied into much smaller reactors than R4 with a shorter retention time of 7.5 days and, therefore, would increase the temperature in the reactor slightly. As we wanted full comparable conditions in the reactors, this was not found to be acceptable during the test period.

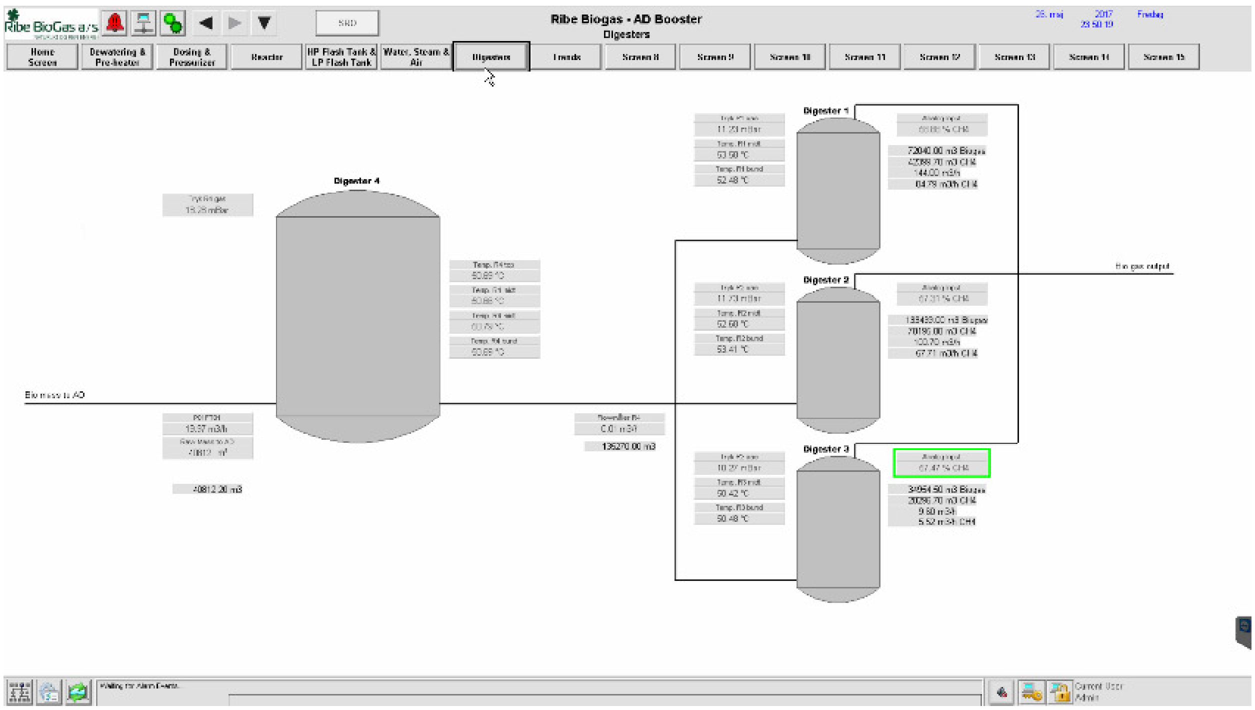


**Figure 1: The reactor set-up at Ribe biogas with one large primary digester R4 (8000 m3) and three secondary reactors R1, R2, R3 (1750 m3 each).**

The test period, which was to demonstrate the actual effect of the AD-Booster-treatment technology on the manure fibers, was started in the beginning of March 2017. When comparing the biogas production of all secondary reactors, we observed a substantial increase in biogas production shortly after pre-treated material had been introduced to R1 and R2.

Before this continuous test for evaluating the effect of the AD-Booster on methane production from normal operation, we did further carry out a test programs with wheat straw and meadow grass. These tests required the installation of a belt conveyer to feed the material up to the 1st floor to the AD-Booster system. The material further had to be pre-cut before transported and was manually loaded on the conveyer, from which it was fed directly into the pressurizer for in-feeding to the AD-Booster.

The tests with straw and grass were aiming on three objectives: Firstly, the assessment of operational conditions related to the handling of dry fibrous biomass materials in the AD-Booster system and the biogas plant. Secondly, defining required modifications of the AD-Booster process for this type of biomass and thirdly, the effect of the AD-Booster on the methane yield of these high-fibrous biomasses.

The low bulk density of both straw and grass revealed that the current feeding system is not optimal for in-feeding this type of bulky biomasses and that the pressurizer could not be loaded with the designed biomass amounts as done with separated manure fibers. With too little in-fed biomass to the reactor system due to the limited filling-degree of the current pressurizer, it was found that the material received too long retention times in the pressure tank, and the extra gas produced- even still significant higher than for straw without treatment- was less than the results found with manure fibers. This result is in contrary to the previous experiments done in pilot scale and clearly show that modifications is needed if the current system should be operated directly on dry biomass materials. These limitations can be overcome by basic modifications of the pressurizer, or more simple, by feeding of the straw to the biogas process upfront before the AD-Booster. In this way even dry deep-litter with high straw concentrations performed well in the current AD-Booster after being through the primary digestion step in Ribe.

Parallel to the operation of the AD-Booster, laboratory tests were carried out at AAU. For this purpose, samples from various sample points were taken at Ribe biogas plant, following specified procedures and schedules. All samples were analyzed for total and organic dry matter content and biomethane potential tests (BMP) were conducted in batch tests. The production of representative samples proved to be difficult as analysis of the samples revealed high fluctuations in dry matter content and methane potential. It became clear that such static tests using small sample volumes could only provide "snap-shots" of the process, which were not suitable to represent the actual process conditions at Ribe biogas. Limitations in the sampling procedure, non-quantified recirculation flows within the biogas plant and insufficient mixing at some sample points obstructed a reliable assessment of the AD-Booster performance in such small batch tests.

To overcome these obstacles, continuous anaerobic digestion trials were carried out in parallel to the controlled test period at Ribe Biogas during the spring of 2017, replacing the batch tests. With a continuous process at bench scale, running over several months and utilizing large sample amounts, AAU were able to obtain reliable stable data supporting the positive results from Ribe Biogas with respect to the effect of the AD-Booster on the methane potential.

**Assessment of project implementation and associated risks**

The AD-Booster system proved to increase the biogas production from manure fibers significantly in demonstrations scale, confirming a successful implementation of the project as a whole. A major concern was that the system wouldn't give the same increased gas production as found in laboratory and pilot scale. However, the results obtained did not only verify the original laboratory results, but further showed consistent additional methane production, whenever the plant was re-started after a short break for maintenance.

A potential obstacle for the applicability of the AD-Booster technology was a high energy consumption that might weigh out its positive effect on methane production. After optimizing the biogas consumption for producing steam to the AD-Booster, 13% of the additional methane produced was used for steam production. In methane equivalents, the overall energy consumption was 15%. In conclusion, the energy consumption is not prohibitive in any ways for the AD-Booster technology.

As the AD-Booster is composed of many separate units, another concern was that these units did not function individually or together. However, the AD-Booster system as a whole was found to be operational from day 1 and after 3 month of optimization the system was capable of long-term operations with some small downtimes for maintenance and repair.

A further concern was that the AD-Booster as a high-pressure system is too complex a technology to operate for biogas plants personnel. After 1 year of operation, we do not anticipate that biogas plants will operate AD-Boosters in the near future. Instead, we are currently marketing AD-Booster plants with an operational contract where the biogas plant has minimal responsibility for the operations of the AD-Booster plant. BioVantage.dk is currently building an operational team, which will be responsible for operating the AD-Booster at Ribe Biogas and all future AD-Booster plants.

Finally, a potential risk was that the AD-Booster technology is a major investment and a too high risk for biogas plants to be able to find funding for buying an AD-Booster plant, even after successful demonstration at Ribe Biogas. When BV started its work with the EUDP project for implementation of the first AD-Booster plant, the idea was that a successful demonstration immediately would lead to sale and customers. During the last 6 months, it has been obvious for the company that a successful demonstration of the technology at the tested 2 ton/hour scale will not be sufficient to allow customers to invest in installation of AD-Boosters in sizes of 12 ton/hour or more as will be needed for some of the largest Danish biogas plants. The company has therefore decided to collaborate up with a large biogas provider in Denmark to build a 12 ton/hours AD-Booster plant financed by outside investors. As part of this strategy, the AD-Booster at Ribe Biogas will be enlarged to a 3 ton/hour system and the 12 ton/hour system will be built as two units with a capacity of 6 ton/hour each.

## 1.5 Project results and dissemination of results

### The performance of the AD-Booster at Ribe Biogas

The operation of the AD–Booster at Ribe Biogas demonstrated that the AWEx pre-treatment technology significantly increases the methane production from manure fibers. After optimization of the demonstration scale plant, the effect of the AD – Booster proved to have superior ability to enhance the anaerobic digestibility of lignocellulosic biomass.

In the tested process configuration, digested manure from Ribe’s primary reactor (R4) was separated by a screw press and the solid fraction was fed to the AD-booster. The boosted solids were then mixed again with the liquid fraction and fed into one of the secondary digesters (R1) at Ribe. This configuration (illustrated in Figure 2) aimed on the central objective of the project: to demonstrate the ability of the treatment technology to transform lignin-rich, recalcitrant fibers into readily convertible substrate for anaerobic digestion.

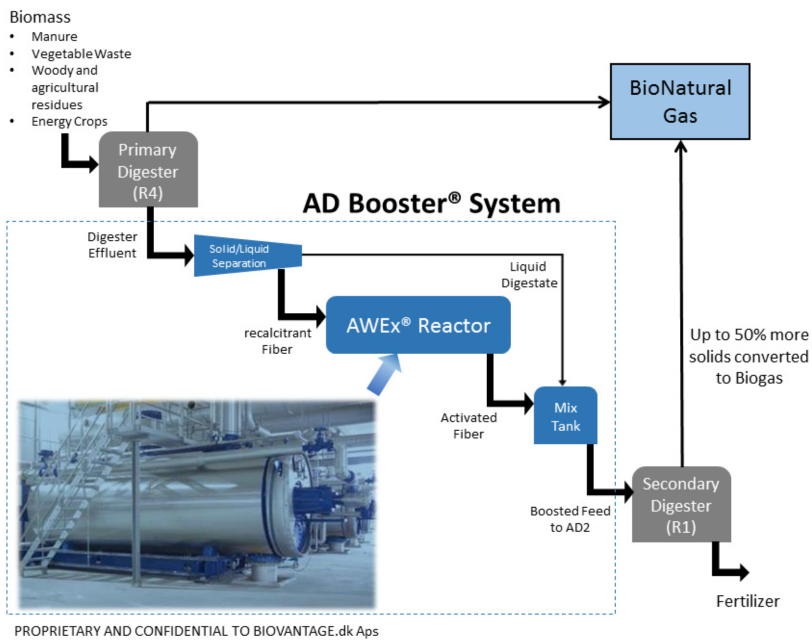


**Figure 2: Process configuration with the AD-Booster inserted between primary and secondary digestion stage.**

While R1 was fed with boosted material, another secondary digester (R3) received feed directly from the primary digester, bypassing the pre-treatment. The gas production rates from R1 and R3 were used to quantify the increase in methane production. Figure 3 displays the effect of the AD-Booster on the methane production in the secondary digestion stage. The graph presents 5-day averages of methane production rates and yield as well as the operating times of the AD-booster. During periods of continuous AD-Booster operation, R1 produced approximately 2.5 to 3 times more methane than R3. Moreover, R1 obtained a higher conversion rate of volatile solids and increased the specific methane from 90m3 CH4/ton VS to 220m3 CH4/ton VS.

The impact of the AD-Booster treatment on the methane yield is further indicated by the steep increase in biogas production when resuming the operation after downtimes of the system (e.g. at hour 1400). These downtimes represent periods where the system is being serviced or changes are being done for optimizations of the process. After each downtime, the methane production rate settled on a slightly higher level than before the interruption. This progression indicates that optimizations had been successfully accomplished and illustrates the advancing increase in the AD-Booster treatment efficiency during the course of the test phase. In the last of the test period, the AD-Booster performed with the highest methane yield and with full consistency (during 1550 and 2000 hours of operation). At 2020 hours of operation, the AD-Booster was shut down to test the response period needed before the systems were approaching each other. As seen from the figure, the gas production in Reactor 1 decreased immediately and the gas production approached the production in R3 within one week's time corresponding to the retention time of these reactors meaning that only low concentrations of fibers persisted in the system at that time.

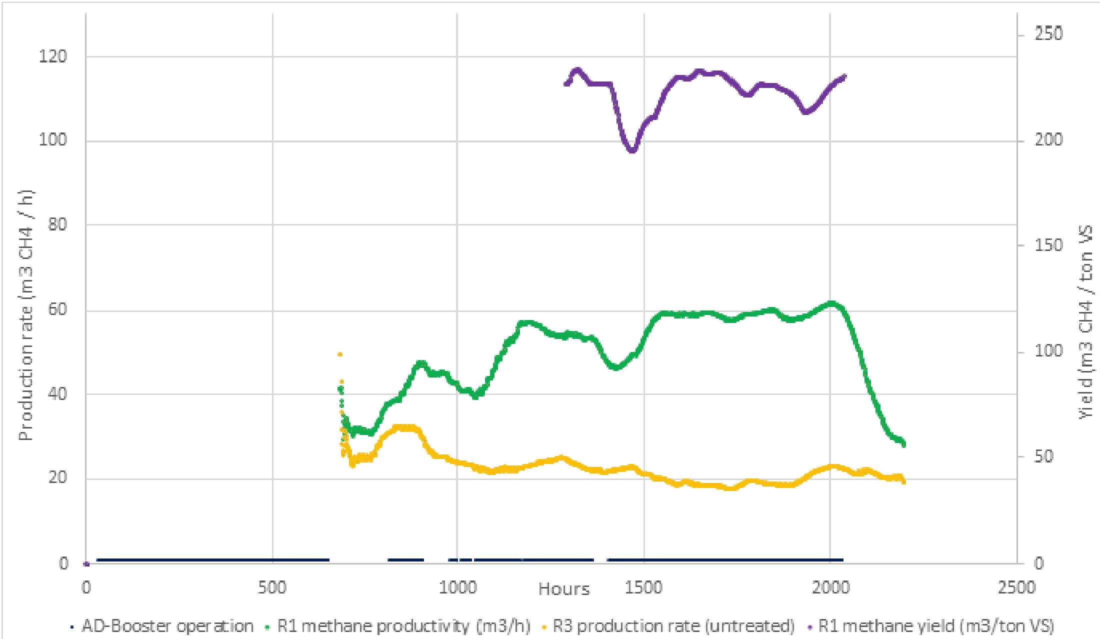


**Figure 3: AD-booster operating times and comparison of the methane production from Ribe's secondary digesters. R1 received boosted digestate; R3 was fed with untreated digestate.**

The additional biogas production derived from boosting the feed enabled Ribe Biogas to reach the target daily gas production without the addition of high-yielding co-substrates such as industrial organic residuals. These substrates are commonly used to supplement the relatively low-yielding manure feed and represent an additional cost for many biogas plants. With the AD-Booster, Ribe Biogas is now able to operate with low-cost substrates such as deep litter and other low cost fibers such as meadow grass. In this way, the AD-Booster reduces feedstock expenses while maintaining the revenue from methane production. Likewise, the AD-Booster technology can expand the substrate portfolio of biogas plants, allowing a higher share of previously unexploited substrates to be suitable and profitable for biogas plants with an AD-Booster. A wider range of low-cost suitable biomass could potentially give rise to growth of the entire biogas sector and also outside areas with large amounts of manure.

### Solid-liquid separation

The screw-press separation was applied on the digestate flow coming from the primary digester (R4) in order to supply the AD-Booster with high-solid feedstock, containing most of the fibres found in the material (Table 1). On average, the separation yield of 30% total solids (TS), supplying the AD-booster with 4114 tons/year of organic dry matter (VS). In total, the screw-press made 47% of the VS available for the AD-Booster treatment. Accordingly, the liquid fraction still contained a considerable amount of solids, which bypassed the AD-Booster. We expect that the separation has a high potential for optimization through technical adjustments of the screw-press and additional measures, which is an area, we would like to optimize in the future. Increasing the separation efficiency will maximise the fraction of recalcitrant solids available for the AD-Booster treatment. It is, however, important to understand that more solids will demand a larger AD-Booster- and we do expect, that there will be a limit to the particle size, which will be beneficial to treat in the AD-Booster.

**Table 1: Mass flows of solid and liquid fraction at Ribe Biogas**

| | Volume | TS | | VS | | Flow |
|---|---|---|---|---|---|---|
| | m3/year | % | tons/year | % | tons/year | t/h |
| Total | 199 993 | 6,1% | 12 179 | 4,3% | 8 662 | 23,81 |
| Liquid fraction | 181 725 | 3,7% | 6 698 | 2,5% | 4 548 | 21,63 |
| Solid fraction | 18 268 | 30,0% | 5 480 | 22,5% | 4 114 | 2,17 |

## Technical Performance and maintenance

The technical integration of the AD-Booster system into an operating biogas plant was successfully accomplished and the system generated positive results from day 1 of operation. Minor adjustments had to be made in order to optimize screw press separation and steam and oxygen generators. Optimizations were implemented throughout the start-up and test phase, causing minor process interruptions.  The AD-Booster has been in continuous operation for nearly a year with only small down-periods for maintenance and repair. The last 5 months was the test period where we finally had the gas meters fully functional and were capable of direct side-by-side comparisons. Through the employment of a remote control and online monitoring system it was possible to operate the system with low labour input.

## Verification of the process performance by continuous lab trials

Parallel to the test phase at Ribe Biogas, laboratory analysis were carried out at AAU Copenhagen and AAU Esbjerg. The objective was to evaluate the performance of the AD-Booster and to validate the results obtained from the operational data at Ribe. Sampling was done at Ribe Biogas of all the fractions around the AD-booster system and a continuous 3-month trial with two bench scale CSTR reactors (Figure 4) was further operated. The reactor receiving pre-treated manure fibers along with liquid yielded 1.5 times more methane compared to the control reactor fed directly with R4 material. Compared to the results from Ribe Biogas, this result showed the same- but lower- positive effect than found at Ribe biogas. However, the amount of extra gas is totally depended on the mixing ratio between the pre-treated fibers and the liquid fraction separated upfront, which was re-mixed in the laboratory based on the one-time split-test. In the one-time split test done by AAU the TS/VS of all fractions around the AD-Booster were determined. From this study the fiber content in the feed was determined to make-up 7% of the material going to the secondary reactors from the AD- Booster. Consistent data from Ribe biogas did show that this figure was over 9%, which fully explain the differences measured (the main amount of organics will be in the fiber fraction). Fully aligned with this, calculations of the methane yield of the fiber fraction from figure 5 A shown in figure 5 B (ca. 200m3 methane/ton VS fiber), is fully consistent with the methane yield calculated for the fibres after pretreatment in R1 as shown in figure 3 (ca. 200 to 220m3 methane/ton VS fibers). In conclusion, we have found that the calculated methane yield of the fibers are similar no matter if a unit of pretreated fibers was tested in the laboratory or at Ribe biogas. The effect of AD-Booster treatment found at Ribe biogas is, therefore, similar to the effect found on fibres tested in the laboratory and all together, the laboratory results fully verified the overall hypothesis of the project.

**Figure 4: Verification of the AD-Booster effect with bench-scale reactors at AAU**

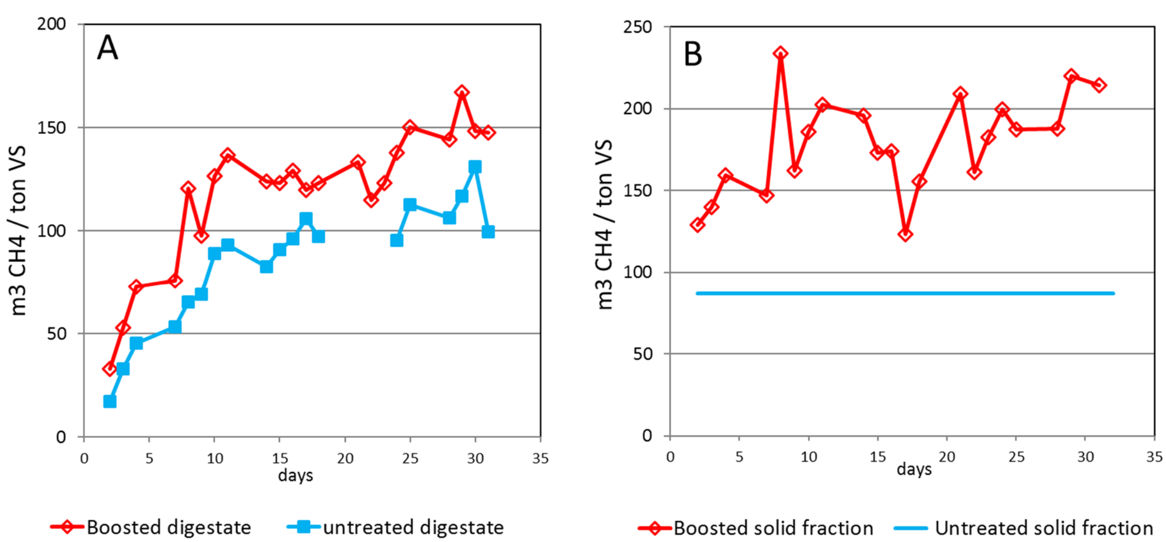


**Figure 5: Total methane yields (A) and theoretical yields for the solid fractions (B) achieved in the continuous digestion experiment.**

*October 7, 2017.*

## Additional analysis

Enzymatic hydrolysis of untreated and boosted samples of digested manure fibers using cellulases and hemicellulases revealed a substantially higher sugar release for the boosted samples compared to untreated samples. After the AD-Booster, the amount of released sugars were 68% (glucose) and 72% (xylose). In all untreated samples, only marginal amounts of sugars were released. These results provide additional prove of the ability of the AD-Booster to make recalcitrant biomass available for enzymatic attack, an important part of microbial conversion.

Selected samples of digested fibres were analyzed for hydroxymethylfurfural (HMF) and furfural before and after pretreatment. HMF and furfurals can potentially be produced during high-temperature exposure and can potentially inhibit the subsequent anaerobic digestion. However, the analysis of the material at AAU indicates that furfural concentrations in all samples were well below inhibitory levels, while HMF was not detected at all. We, therefore, conclude that the AD-Booster does not introduce any adverse effects on anaerobic microbes.

## Pre-treatment of meadow grass and wheat straw

The handling of both wheat straw and meadow grass was clearly facilitated by the AD-Booster treatment, as particle size and viscosity were reduced. This enables biogas plants design for manure digestion to process biomass with higher fibre content.

However, the low density of the straw and grass (when compared to manure fibers) required a larger pressurizer and a longer in feeding time in order to maintain the appropriate loading of the AD-Booster. In the current system, low feeding rates will lead to unfavourably long treatment retention times, which lower the effect of the AD-Booster. This was confirmed by continuous lab trials with pre-treated straw, which indicated a lower effect of the AD-Booster, when compared to the results found with manure fibres tested in the same reactor set-up. It is anticipated that a large pressurizer would solve the problem with in-feeding of dry biomasses such as straw and grass directly without previous digestion and allow for extra gas yields significantly higher than the ones obtained with manure fibres.

## Comparison of the AD-booster to other lignocellulose treatment methods

Among the widely reported treatment methods for fibres tested at lab scale, only few mechanical, thermal and thermochemical methods have been successfully applied at full scale. For lignocellulosic material, thermal pretreatment has been studied extensively and is widely considered advantageous to most other traditional methods as e.g. mechanical or chemical treatment [1]. Demo-scale facilities such as the Inbicon plant in Denmark and the Beta Renewables' Crescentino plant in Italy have proved that thermochemical methods are applicable for making biomass accessible for further degradation [2, 3]. However, high capital and operational costs as well as limitations with respect to the range of biomass types and sensitivity to soil and sand are often claimed to be the main problem obstructing a wider application of thermochemical methods during biofuels production [4, 5].

The AWEx pretreatment on the other hand, can handle a wide range of biomass, including woody biomass and a majority of agricultural residues [6]. The technology requires less energy input due to the exothermic reaction taking place in the process and has moderate capital costs. The use of oxygen as an oxidizing agent has an influence on operational costs, but the high performance rate of the process can offset these extra costs.

**Dissemination**

BV has presented the AD-Booster at many meetings during the EUDP project, including seminars for biogas operators. The demonstration plant has further been presented in different arrangements for potential customers and their technical staff. Additionally, in September 2017 the plant has been presented at the Interreg seminar under the EUROPEAN COOPERATION DAY. The seminar featured a full day excursion to Ribe biogas with a visit to the AD-Booster plant. Here the AD-Booster Facility was featured as the future of biogas production where the participating organizations where given a detailed tour of the AD-Booster facility. The tour also offered a first-hand impression of the effect on the fibers before and after AD-Booster treatment by visual and manual inspection of the different fractions of the process. Finally, the tour included a short introduction to some of the results from the project.

The participants for the Interreg included Lemvig Biogas, Nature energy, North Tech, Hochschule Flensburg, Aalborg University Esbjerg, Ribe Biogas, Dansk Fagcenter For Biogas, Hamburg University of applied science, Sønderjysk Biogas Bevtoft, Lund University, Roskilde University, Alborg University, Linkogas, A.m.b.a., Cir-Tech, Agrinord, Biofuel Technology, Somsoe Kommune and University of Southern Denmark further visited the AD-Booster in the spring of 2017. The tour was followed by a short session with an open discussion of pro and cons for the AD-Booster system. As part of these showings, many potential customers showed interest in implementing the AD-Booster at their biogas plant.

### 1.6 Utilization of project results

In the original proposal, the pathway for further disseminating the results from the project was clearly outlined. In accordance with the original plan, we held a large number of showings of the AD-Booster demonstration plant to potential customers in the spring and summer of 2017. Besides, we showed the AD-Booster plant during workshops and national and international meetings held by different organizations and received many requests for information because of these meetings. Just before summer, a memorandum of understanding was signed with two different large biogas plant owners having several Danish biogas plants in operation and new plants in construction. During the following discussions, it became obvious to us that the scale up factor from the AD-Booster at Ribe Biogas to the large commercial size needed for some of the newest and large Danish biogas plants was extensive (12 ton fiber/hour compared to 2 ton fiber/hour at Ribe Biogas). It was therefore, decided that we would Built, Own and Operate (BOO) the first large AD-Booster plant exactly the same way as we have done with for the Ribe demonstration plant. After this plant would be in successful operation, the road to wide market access would be fully open. As a result of this decision we picked one of the potential collaboration partners, who had already been in the loop, to continue discussions on our next large scale AD-Booster BOO plant.

During the last month, we have together with our new partner produced a Prospectus over the new AD-Booster plant including siting, flow of fibers and dry matter, integration with the existing biogas plant, operational procedures, economics including operational cost etc.

BioVantage.dk has further secured funding for this new facility as a mixture of loans and investor input. It is important to understand that this financing would never have been possible without the demonstration facility at Ribe Biogas and the long-term data obtained from this plant, which shows that the AD-Booster technology has a very attractive Internal Revenue of Return (IRR) necessary for securing investments. A model for determination of the extra methane produced due to the AD-Booster plant has further been developed as well as the model for sharing the profit from the extra gas produced. The partners are currently working towards a closing of their internal contract before Mid-November and start-up of construction is planned for the beginning of next year. To conclude: the project has led to commercial activities and it is obvious that the AD-Booster technology will be capable of widely penetrating the market especially for large biogas plants, when the new expanded large scale AD-Booster plant will be in operation before the end of 2018.

The change from a general sale of plants to targeted construction of BOO plants has a number of advantages at this stage. It is obvious that the success of the AD-Booster facility at Ribe Biogas is due to the fact that BioVantage.dk have had the overall responsibility for all parts of the construction of the plant, the start-up and finally long-term operation of the facility. The company used an experienced supplier for the high-pressure parts of the AD-Booster plant, but overall BV took care of all connections of the many different parts of the plant as well as the overall steering system. The AD-Booster plant has many different parts, which need to be coordinated for optimal operation. In most cases, we were able to solve this task within the very tight timeline made originally as we had full control over all the integrations. We further found that optimal operation of the AD-Booster plant over extended periods demanded that BioVantage.dk had the overall responsibility for the operation of the plant. Ribe biogas provided daily support and oversight under the management of BV personnel and were active in determining all technical changes done to their plant for operating the AD-Booster.

The market potential for the AD-Booster facility was outlined in the original proposal. Since then 15 new Danish biogas plants have been constructed or are under construction. The German market seems to move more slowly currently due to new restriction on using maize silage as a major input to biogas plants, which was practiced until recently. The AD-Booster is an obvious solution to this problem as it will be capable of securing the extra methane needed in these plants for a positive economics with manure or other low cost materials such as meadow grass and straw as major raw materials.

Until now, no new competitors has entered the market. The overall process used is patent protected and BioVantage.dk is focused on ensuring that some of the new major discoveries will be further patented to strengthen the company's position on the market. We believe that these patents will give us a major advantage also in a situation where a new unknown technology would be developed by others in direct competition with our process. Overall, the EUDP partners in the demonstration project have shown results from the project at meetings and conferences and prepared publications. It has, however, been decided that a widespread press release with broad public appearance will await the opening of the new large AD-Booster in 2018.

The AD-Booster technology is directly aligned with the Danish/European energy policy and will help us decrease our dependence of fossil fuel with a lowering of our greenhouse emission.

*October 7, 2017.*

As the technology allows for production of far more biogas/methane from material such as manure, which has no other uses and no conflict with food or feed, the technology has a potential for significantly reduction of our carbon footprint. Compared to conventional biogas production the AD-Booster is a far greener technology as their will be reduced need for transport of materials to and from the plant. The technology just allows for a better use of the materials already found at the biogas plant.

## 1.7 Project conclusion and perspective

The EUDP project was intended as a demonstration of the AD-Booster technology in small commercial scale to verify data previously obtained in laboratory and pilot scale. The project was executed in accordance with the original plan and time schedule. Results from an extended test period where parallel reactors were run in a side by side manner verified that the AD-Booster increases the biogas/methane production significantly of the fiber fraction. For a biogas plant operated in the same way as Ribe biogas this means that an AD-Booster handling all fibers from the plant has the potential for increasing the gas yield of up to 30%. The project did further produce valuable data for operational and maintenance cost of the AD-Booster operations necessary for commercialization of the technology. Due to the positive results obtained in the project, the AD-Booster technology is now on its way into the biogas market and the partners anticipate that the technology will penetrate widely during the coming years.

**Acknowledgement.**

The partners would like to thank EUDP for their support. Without this help, the AD-Booster technology would never have reached the same maturation in such a short time frame.

A special thanks to Stefan Heiske, AAU for his major effort during the reporting phase.

## References

[1] Javkhlan Ariunbaatar, Antonio Panico, Giovanni Esposito, Francesco Pirozzi, Piet N.L. Lens*, Pretreatment methods to enhance anaerobic digestion of organic solid waste*, Applied Energy, Volume 123, 2014, Pages 143-156

[2] Larsen J, Haven MØ, Thirup L., *Inbicon makes lignocellulosic ethanol a commercial reality*. Biomass Bioenergy Volume46, 2012, Pages 36–45

[3] Janssen R, Turhollow AF, Rutz D, Mergner R, *Production facilities for second-generation biofuels in the USA and the EU— current status and future perspectives*. Biofuels and Biorefinery Volume 7, 2014, Pages 647–665

*October 7, 2017.*

[4] Zheng Y, Pan Z, Zhang R, *Overview of biomass pretreatment for cellulosic ethanol production*. International Journal for Agriculture and Biological Engineering, Volume 2, 2009, Pages 51–68
[5] Balat M, *Production of bioethanol from lignocellulosic materials via the biochemical pathway: a review*. Energy Conversion Management, Volume 52, 2011, Pages 858–875
[6] Biswas, R., Uellendahl, H. & Ahring, B. K., *A Universal and Efficient Pretreatment Process for Lignocellulosic Biorefineries*, BioEnergy Research Volume 8, 3;  2015, Pages 1101-1116

*October 7, 2017.*