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Exploring Expansion of Biogas Energy Production on Homesteads, Small-Scale, and Large-Scale Farms

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I. Introduction

Biogas is a source of renewable energy which captures methane gas produced by manure, sewage, and food waste to generate energy [1]. The overarching goal of this project is to develop a comprehensive understanding of how biogas is viewed and portrayed by different groups, how the use of biogas differs from large-scale to small-scale farm and homesteading operations, and how biogas can more effectively be used. Essentially, the goal of this research is to lay the foundation for members of the sustainability community at large to better understand the economic feasibility and practicality of biogas at different use scales, in the hopes of achieving wider implementation of this source of renewable energy.

Energy production impacts everyone, so alternative sources of energy are certainly an interest across many fields. The operation of biogas also has numerous, direct economic benefits to private individuals. Just a few of these include reduced reliance on the electricity grid, decreased costs associated with waste disposal, and the potential for other sustainable practices like reusing biogas slurry for effective fertilizer. [3]. However, small-scale biogas energy production in the US is surrounded by a lack of literature. Although research on the science behind biogas is adequate, much of the existing literature regarding its social, cultural, and economic benefits is from large-scale operations in Europe and private use in developing countries [2]. Research done by Bucknell students in past years investigated existing knowledge of biogas [1], where it is currently implemented [6], and what the perception of biogas is in the media [4]. The overall result of these studies is that existing information, primarily from government and industry, on biogas as an energy source is insufficient to support the implementation of small-scale plants on farms or in homes in the US. This research centers specifically on how this information deficiency impacts public understanding of the true economic feasibility of biogas for private energy production in the US and is intended to expand that information through a multifaceted approach.

Emmanuel Yiridoe and others note that increased support of sustainable energy has resulted in farmers and private individuals turning to renewable energy sources that have previously been considered "technologically infeasible and/or economically not viable" [11]. Biogas is one such source. In a past research project completed at Bucknell, Suphanat Juengprasertsak and others concluded that there is no policy supporting small-scale biogas energy, and that people are unfamiliar with implementing these systems on a household scale [6], a fact which is reinforced by existing literature focused primarily on large-scale biogas intended for electricity generation. During a literature review, multiple studies cited various farm sizes as the minimum requirement for an anaerobic digester to be economically viable. These recommendations conclude that anywhere from 250 [7] to 3000 [8] cows are necessary for farmers hoping to utilize their manure for digestion.

However, a variety of studies done on international, small-scale use of biogas demonstrate that it is, in fact, both feasible and practical [6]. Dr. Shaunna Barnhart, the professor advising this work, completed prior work on household biogas in Nepal [2], which formed a basis for the inspiration behind this work. Additionally, much of the networking completed during this project was done with the assistance of Solar Cities, a "US-registered charity focused on delivering biogas solutions within the USA and across the globe" [5]. While the organization's work with anaerobic digestion in the US has expanded rapidly over the past decade, their work is international and utilizes the existing state of biogas globally to create partnerships and foster learning.

II. Methodology

The purpose of this research was to compare existing data on large-scale farms with anaerobic digesters in Pennsylvania to small-scale farmers and homesteaders without equivalent representation in discussions of biogas in a US context. This research took a dual approach to collecting data for a variety of reasons. The first method of data collection was a survey, drafted and distributed early on with the intention of receiving as many responses as possible. The second approach was semi-structured interviews, which occurred either on-farm or via Zoom. The survey and interview protocols were approved by Bucknell University's Institutional Review Board under IRB #: 2223-156.

i. Survey

The survey was open not only to current biogas practitioners, but also anyone with an interest in the subject. Sections included "Your Anaerobic Digester," "Energy Dependence," and "Climate Change and Sustainability." Respondents without an anaerobic digester of their own only answered questions from the relevant sections regarding their perspective on renewable energy in general.

One primary question type on the survey asked respondents to answer an open-ended question regarding their anaerobic digester or other features of their sustainable lifestyle. These questions were initially grouped into brackets for variables such as cost and size, but due to the wide range of digester models and costs, they were changed for respondents to answer freely. The second main question type had respondents rank their experiences and opinions on Likert scales. Some of these involved participants' perception and experience with quantifiable variables like return on investment or grid reliance, while others asked their opinion about topics such as climate change, sustainability, and the perceived impact of their digester on their community.

The general purpose of the survey was to collect quantitative data from a number of respondents across all farm sizes. To accomplish this, it was distributed through a variety of methods with varying degrees of interaction.

Because case studies and other records exist for large scale digesters, a list of those farms for sampling was pulled from the AgSTAR database, a collaboration between the EPA and USDA designed to "assist those who enable, purchase or implement anaerobic digesters by identifying project benefits, risks, options and opportunities" [9]. These "large-scale" farms are primarily dairy farms with anywhere from 300 to 3000 cows. Due to the inherent business of the summer season for these farmers, paper copies of the survey were mailed out to the 30 listed in Pennsylvania with the additional ability to take the survey online with the hope of increasing participation from this sample. Of the 30 surveys distributed to large farms, 5 responses were received, which constitutes a 17% response rate.

For small-scale farmers and homesteaders, the survey distribution and networking used snowball sampling instead. Many of the connections and work done during this research was conducted with the assistance of Solar Cities. The group's home biogas designs, developed and installed around the world by Dr. T.H. Culhane beginning in 2009, have seen a major increase in refinement and implementation over the past decade. Two other co-founders of the organization, Janice Kelsey and Jody Spangler, provided valuable insight and networking opportunities throughout the course of this project. The survey was posted to the Solar Cities Facebook group and a variety of others regarding homesteading and small-scale biogas. Over the course of the data collection, 25 responses were received from small-scale farmers and homesteaders.

ii. Interviews

The second method of data collection was a series of interviews conducted with interested parties. At the conclusion of the online survey, respondents were given the opportunity to list their preferred contact information for a follow up interview if they were interested in sharing more about their experience with an anaerobic digester. This included both large-scale farmers registered to the AgSTAR database as well as small farmers and homesteaders who responded to the survey or found out about the research through Facebook or Solar Cities. Interviews were conducted in-person on some farms and over Zoom for others. While several large-scale farmers expressed interest in an interview, many did not come to completion due to the inherently busy nature of the summer season for commercial farms. A total of 2 large scale farmers were interviewed, and both provided insight into very different experiences with biogas. In addition, 6 small farms and homesteaders were interviewed and several others expressed interest but ultimately faced time conflicts later in the summer. For analysis, interviews were recorded and transcribed.

During the interview process, practitioners were asked a similar set of preliminary questions similar to those found in the beginning portion of the survey. They were asked to describe their digester and its history, their farm, and their primary sources of income (on-farm vs. off-farm). After, participants were asked about the initial purpose of their digester and what their experience has been over the course of its operation. This included questions about their use of the gas and their calculated or perceived economic return on the digester. Over the course of the interview, if they indicated that the digester was installed for energy generation and economic purposes, they were asked to elaborate on their experience with funding and policy. Those who indicated a more environmental motivation were asked to further describe their views on sustainability and the benefits of a digester.

After interviews were conducted, the recordings were transcribed so common themes and quotes could be pulled during analysis. From that analysis, three categories of key points jumped out: motivation, knowledge and maintenance, and economic return. These topics correlate to the survey topics, as views on climate change and sustainability correlate to a person's motivation for building a digester, knowledge and maintenance relate to the specifications of the digester, and economic return is largely based on the energy return of a digester. Each of these was a point on which large-scale and small-scale farmers differed in their experiences or opinions and led to different conclusions on how improvements to biogas in Pennsylvania can be made.

III. Results

As a result of the largely open-ended questions from the survey and the accompanying interview transcripts, the results of this project and the conclusions drawn from them shifted over its course. Initially, the intent was to use quantitative analysis of survey results to form conclusions which could then be supplemented with testimonies from interviewees. However, several factors eventually led the interview responses to generate the primary conclusions from this research. One factor involved difficulty with collecting a large survey sample size. Because the initial sample, biogas users in Pennsylvania, is not an extensive group to begin with, the actual number of responses received constitutes a relatively small group. Another reason individual testimony is more valuable in the lens of examining biogas is that digesters are designed and installed to meet the needs of the homestead or farm using them. As a result, quantitative analysis of size, cost, etc. generalizes a sample which is difficult to represent in such a manner due to the individuality of its responses.

i. Digester Characteristics

Large scale farms with systems ranging from 500,000 gallons to 1.5 million gallons as well as homesteaders and small farms with systems ranging from 50 gallons to 400 gallons responded to the survey. A key characteristic determined by the survey results is that no two digester installations are the same. Size, cost, fuel, and energy use all depend on the individual needs and abilities of their proprietor. This is what results in a wide range of values for each quantitative survey result. Figures 1-3 below depict a few of the various anaerobic digesters viewed during the interview process.

Figures 1-3. Solar Cities IBC backyard digester with floating drum for gas storage (left). Underground IBC digester with gas storage bag (bottom right). Large scale covered lagoon digester (top right).

ii. Motivation

The first difference between large-scale and small-scale farmers lies in their motivation. In the Expansion of Biogas survey, respondents were asked to rank the importance of a variety of factors in their decision to build an anaerobic digester. The results with a statistically significant difference in the responses from the two groups are displayed in Figure 4 below. Large scale farmers indicated that generating income and odor reduction, a part of required manure management plans, were significantly more important to them. In contrast, small-scale farmers and homesteaders indicated a greater influence by desired self-reliance and energy independence, environmental conservation, and concerns about climate change.

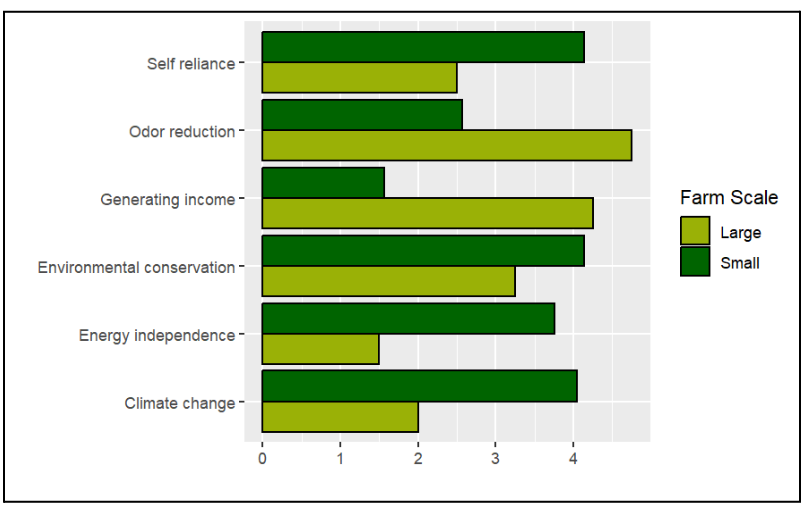

*Figure 4. Comparative chart of responses indicating the importance of issues to respondents on a Likert scale of 1 (not at all important) to 5 (very important). *Includes only issues with a significant difference (<0.05) between large-scale and small-scale responses.*

These quantitative results were certainly reflected in the responses given in the interviews as well. The small farmers, especially those involved with Solar Cities and its associates, generally placed finances much lower on their list of concerns. A large portion of that is due to the significantly lower investment as opposed to large digesters, but also the influence of the sustainability community and the role it has played in expanding the use of home biogas digesters. Other motivations that were mentioned by the interviewees included learning and teaching opportunities. Kathy Puffer, a co-founder of Solar Cities, wrote,

> *"I am grateful for all of the learning experiences that I've had and continue to have…each repair and parts replacement placement provides me with new content to share with a growing group of students, so I consider it all an investment instead of a loss."*

Adam Dusen of Hundred Fruit Farm in Buckingham, PA also said,

> *"Cooking for gas seems really easy and straightforward and the best way. But the other really big value for me is just educational, because we do run courses here. We have students coming here all the time, we have interns. So it's just a really cool thing to be able to show someone at a permaculture course that, hey, let's talk about appropriate technology and alternative energy sources and then, you know, be able to show them one that's in use on the farm."*

iii. Operation Knowledge & Maintenance

The second difference in the experiences of operating anaerobic digesters on different scales is the knowledge and maintenance required for the systems. First, the large differences in size between digester types mean corresponding differences in material, number of moving parts, and access. Second, the previously noted differences in motivation for farmers and cost also seems to correlate with knowledge of the basics of biogas and degree of hands-on approach. The majority of large-scale farmers who responded utilized a mix of state and federal grants in addition to bank loans and self-financing. In correlation with the grants received, these large-scale systems are often installed entirely by a third party, so maintenance must accordingly be exported to a third party as well.

Over the course of the interview process, two farms had exceptions to this. In one, the initial digester design was created and then built by a family member with a history of engineering. As a result, the digester was entirely self-financed and maintained over his tenure at the farm. However, without an on-site presence able to diagnose and fix any issues with the digester, investing additional money into hiring someone for maintenance was not worth it.

He noted,

> *"Once we removed the original operator who was operating as just part of his job and his other duties, paying somebody else of that type of engineering experience just didn't pencil out in terms of what our electrical costs actually were."*

In the other exception, the farm owner uses prior training as a mechanic to do much of the labor himself. Additionally, for both of these farmers, the electricity generated by their digesters was used to offset their on-farm costs. This means that they do not receive additional profit from the digester, so any maintenance costs are out of pocket, even if the initial investment for the digester was aided by government grants. According to this farmer,

> *"If you didn't factor labor into the cost, then it was worth it, but now that we would have to pay somebody to operate it, it's no longer worth it at all."*

So, not only is the initial investment for large digesters higher, they cost more to fix and actually seem to break more often. The reason for this is likely that, in order to avoid clogging and to keep solids in the tank evenly distributed, larger tanks require moving parts to agitate the digestate. On a smaller scale, a pipe can be built into the tank and solid material can be agitated by hand using a rod. As a result, the Solar Cities IBC designs and other small digesters have essentially no moving parts. Among the small farmers interviewed, many noted that the only maintenance required so far is replacing seals here and there to keep everything air tight. Kathy Puffer, who started out on the ground floor of the Solar Cities initiative, has an older model of their IBC digester in her home. She explained that she has had many more maintenance problems, but she was able to solve them with DIY methods and that the technology involved with home biogas has evolved and improved over time. Janice Kelsey and Kathy Puffer, two of the other founders of Solar Cities, elaborated thoroughly on the benefit of these simpler systems and the absolutely minimal maintenance they have had to do on them.

> *"The mechanics are so simple, and the reason we were trying to keep it simple is so people could actually build them...you want the bare minimum of what works...and I haven't had to do much maintenance on it."*
>
> ***-Janice Kelsey, Solar Cities co-founder***

> *"If it's mostly a DIY system, there's definitely room for accessible technologies that people would be able to do...We do not have maintenance issues, not at all, because it digests so well."*
>
> ***- Jody Spangler, Solar Cities co-founder***

iv. Cost and Economic Return

The final key difference between large and small-scale farmers over the course of this project was in the costs of their system and the economic return from it. Understandably, large scale farms using digesters to support commercial farming and sell energy back to the grid have much higher upfront costs. This is reflected clearly in the existing literature that is available for interested parties. The large scale farms in this study spent between $1 million to $3 million to build the systems, with a combination of self-finance, bank loans, and/or government grants. However, after speaking with a few of these farmers and receiving survey responses from more, many farmers feel that there have been further costs associated with their systems that were unclear during their initial implementation. As previously discussed, maintenance costs are extremely high for these digesters, and the larger the digester, the more moving parts there are to require regular maintenance. Additionally, without experts available on-farm, further money is required to hire outside help for maintenance. A key point which multiple commercial farmers made clear is that, while grants helped to alleviate their initial costs and decrease their personal investment, no assistance is available for continued maintenance. This presents a myriad of additional, unseen costs that may not have been considered. Furthermore, as one farmer pointed out, to receive the initial grant money, their farm was required to sign a contract to keep their digester operational for twenty years, guaranteeing further personal investment down the line. All this together with the case that many farmers use the digester to simply offset their farms energy costs and not for profit, make the case of economic return a hard one to evaluate. One large-scale farmer said about his experience:

> *"We don't make a lot of surplus, but we make easily enough to supply our farm...We thought it would be better than it is...If you didn't factor in labor into the cost, then it was worth it, but now that we would have to pay somebody to operate it, it's no longer worth it at all."*

In contrast, over the course of interviewing small farmers and homesteaders, the overwhelming response was that the small digesters are very much worth the investment. All of the small scale systems reported in the survey and interviews cost less than $1,000 to build. Not only is there a lower upfront investment, but the community surrounding home biogas, like what Solar Cities does, allows for discussion with others, shared designs, and even help installing and maintaining the digester. It is notable that a portion of this perception of economic return from the digesters is also connected to the motivation people have for pursuing anaerobic digestion at their home. For many, the sustainability and education components alone make it worthwhile to them. However, practically, almost every interviewee with a small digester said that, without a doubt, the offset of heating and gas bills has easily returned their investment. Janice Kelsey described,

> *"I mean, honestly, even if you're not looking at it as like, I want to make money off of this or save money on my electric bill, just having that zero-waste cycle of food*

> *from the kitchen going back into cooking for it. I feel like that automatically makes it worth it….[and] I've definitely gotten my money back."*

Additionally, if costs still remain a concern for interested parties, Solar Cities and other groups like them have a passion for their work and a willingness to assist in making these digesters as accessible as possible. One farmer who was interviewed noted that he hosted a workshop with a group interested in building their own digesters, and a minimal fee helped to offset the cost of the one being installed. Finally, as another key point important to why small-scale biogas is only becoming more cost effective, compact sizes and simplistic design mean these digesters are able to constantly be improved and updated as new designs are worked out and others recommend practical solutions to any existing problems. On a large-scale, digesters are nearly impossible to update or replace with the enormous costs involved and the time frames each one is designed for. One large-scale farmer noted that, when he took over operation of their family's farm and its digester, the model was outdated and inefficient, but the cost to take it out and replace it was much too high for them to consider, so the digester has been out of operation since.

Overall, outside of farmer's motivation for using biogas, cost is important to everyone. Therefore, making biogas more accessible through everything; including design improvement, awareness, and policy and funding aid; is vital to its expansion.

> *"It's the importance of economic feasibility: not everybody has the economic privilege of being able to volunteer and there has to be a model in which people can, one, not lose money, at least break even, and then possibly be able to turn a profit."*
>
> ***- Kathy Puffer, Solar Cities co-founder and biogas educator***

IV. Discussion

The results of this research have more qualitative than quantitative characteristics, but these are quite valuable based on key results taken from the survey conducted. One key result of the survey is two questions which asked respondents to rate their overall satisfaction and satisfaction with the return on their investment on a Likert scale of 1 to 5. From those responses, an average level of satisfaction both in general and for the economic component of small-scale and large-scale biogas was calculated. Then a significance test was conducted and found that there was actually no significant difference in either level of satisfaction between small and large-scale farmers. Table 1, below, lists the various uses for biogas and challenges faced while operating a digester that respondents gave. Evidently, although there is a clear difference in the way that farmers use the biogas, the challenges they face remain much the same regardless of size.

Farm Scale	Biogas Uses	Challenges
Small	Cooking, heating, lighting, fuel for generators, carbon dioxide for greenhouse supplement	Time, money, support, sourcing materials, weather, space/location, odor, maintenance
Large	Electricity generated for on-site use, electricity generated for the grid	Temperature, maintenance, cost, permits

Table 1. Responses given by small and large-scale farmers on their uses for biogas and the challenges they face in operating a digester.

Another similarity that the two groups have is that the investment required by their digester is equivalent to the potential return it has. Farmers who invest millions offset similarly large amounts in energy costs and give themselves the potential to generate enough electricity to sell back to the grid. On a smaller scale the digester requires less upfront capital, but also offset smaller costs each year. Where the two groups divide can be seen later in the survey and throughout the interviews conducted. They differ in motivation and knowledge, which affects their perception of value outside of just economic return. Several home biogas owners expressed frustration with cost and maintenance issues over time, but said the educational and awareness value has been entirely worth it. In contrast, large-scale farms are forced to focus on the financial aspects of a digester because the investments required of them are much higher. This is also where existing literature on biogas in Pennsylvania and the rest of the US does not reflect the full picture.

Prior to receiving any survey or interview data, research into biogas indicated a situation in Pennsylvania where only large dairy farms had any chance of making anaerobic digestion economically feasible. Now, after speaking with a variety of practitioners about their experiences, it is clear that what publications are out there only represent a small sample of biogas users in the state. The literature seems to be generally skewed to portray biogas as a source of renewable energy only in terms of electricity generation, which leaves out farmers using it to offset electricity needs through heating and cooking using the gas itself. One farmer said about his own experience reading through existing studies,

> *"Whenever I came back [to run the farm], I did a bunch of looking into what it would take to get started again. And, you know, most of the publications seemed pretty pessimistic."*

This discovery clearly demonstrates that one major component to expanding biogas use in Pennsylvania is expanding awareness of biogas in Pennsylvania. There is a community surrounding home biogas that takes its cues from international use of small-scale biogas and is steadily growing. In fact, while many of the large farmers who responded indicated that their experience over time has not necessarily improved their perception of the value of digesters, the small-scale responses were quite the opposite. Solar Cities and its partners have grown steadily over the past ten years and a foundation has been created that allows new users to learn and grow from current ones. Interviews were conducted with users who installed their digester a decade ago and also those who have newer designs that have improved on past mistakes, and a difference is clear to see. Simplicity, ease of use, and the elimination of maintenance concerns have all evolved just recently as small-scale biogas in the US expands. What has been happening recently will continue in the future, and support in the form of policy, grants, and encouragement will only make biogas grow even faster as a valuable solution in the sustainability community.

In the future, there are several ways in which the US has the opportunity to aid the biogas community. In terms of policy, there is none necessarily against biogas, but a general lack of any regulations can make it difficult for practitioners to receive approval and funding. Small-scale interviewees said that the lack of environmental standards surrounding gas production decreases confidence and awareness and prevents government support of urban farming, homesteaders, etc. Large-scale interviewees commented on the lack of funding to support maintenance after the installation of their digesters. They also noted that, while policy in Pennsylvania allows farmers to get funding to install equipment for electricity generation, it does not support the installation of systems for distributing heat outside of what is used immediately by their farm. In general, as knowledge of biogas and policy surrounding it are extremely limited, the best way to support the huge potential biogas has is to start with recognition in literature, government, and the renewable energy industry.

In terms of future research, a continuation of the same kind of data collection done in this project would be valuable. Large-scale biogas is expensive and has certain requirements that make many farms ineligible. As a result, the sample size available for research is small to begin with, and the number of responses received for this project was only a portion of that group. More responses were received from small farms and homesteaders, but micro and nano-scale biogas in the US is relatively new and still growing and changing rapidly. Due to these characteristics, future expansion of data collection would be incredibly valuable to continue to examine changes in economic feasibility, perception of biogas, and technology over time. Additionally, with additional data collection, statistical results will become more significant and valuable over time as the number of available testimonies and case studies expands.

V. Conclusion

The results of this project are not what they were anticipated to be at its start. However, what conclusions can be drawn from this work seem to support the expansion of biogas in Pennsylvania more than what was initially hoped. Initial methods intended to find the data necessary to support the feasibility of biogas on micro and nano scales. However, results demonstrated that proving its feasibility in a statistical sense is unnecessary, because small-scale biogas is already functioning in Pennsylvania. A spatial analysis by Hongyi Wang, completed with Bucknell funding in the past, determined that Central Pennsylvania has extensive potential for small-scale biogas production [10]. Now, this research has demonstrated that potential is already being utilized. The designs for small-scale biogas are sound and support within the home biogas community exists. Now, the next steps are to assist what already exists in becoming recognized and advocated for on a larger scale.

> *"If you're looking at outside people struggling with it, it's finding all the parts you need...other people really just don't understand what it is...It's awareness, they're not aware that it exists, they're not aware that there's an alternative."*
>
> ***- Janice Kelsey, Solar Cities co-founder***

VI. References

[1] Babyak, B., D'Aliso, C., & Barnhart, S. (2017). Exploring benefits, barriers, and perceptions of adopting biogas technology [Poster]. Bucknell Institute for Public Policy: Center for Sustainability and the Environment.

[2] Barnhart, S. (2014). From Household Decisions to Global Networks: Biogas and the Allure of Carbon Trading in Nepal. *The Professional Geographer*, *66*(3), 345–353. doi.org/10.1080/00330124.2013.821720.

[3] Beddoes, J. C., Bracmort, K. S., Burns, R. T., & Lazarus, W. F. (Eds.). (2007). *An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities*. doi.org/10.22004/ag.econ.330474.

[4] D'Aliso, Chris. (2017). NVivo biogas summary: News transcripts [Document review]. 1-2.

[5] *Home—Solar CITIES*. (n.d.). Retrieved August 7, 2023, from solarcities.solutions/?fbclid=IwAR2M7edjoNOGFwKO1FeGnHNHYS8P1rbBqhOYNEzp-StYYl9pVAKPS9liauY.

[6] Juengprasertsak, S., Babyak, B., & Barnhart, S. (2018) Exploring expansion of biogas energy production on homesteads, small-scale farms, and large-scale farms [Poster]. Bucknell University: Center for Sustainability and the Environment.

[7] Klavon, K. H., Lansing, S. A., Mulbry, W., Moss, A. R., & Felton, G. (2013). Economic analysis of small-scale agricultural digesters in the United States. *Biomass and Bioenergy*, *54*, 36–45. doi.org/10.1016/j.biombioe.2013.03.009.

[8] Lauer, M., Hansen, J. K., Lamers, P., & Thrän, D. (2018). Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry. *Applied Energy*, *222*, 621–636. doi.org/10.1016/j.apenergy.2018.04.026.

[9] US EPA, O. (2014, December 8). *What EPA is Doing: AgSTAR* [Overviews and Factsheets]. www.epa.gov/agstar/what-epa-doing-agstar.

[10] Wang, H. (2019) Biogas in Pennsylvania and its possible development [Poster]. Bucknell University: Center for Sustainability and the Environment.

[11] Yiridoe, E. K., Gordon, R., & Brown, B. B. (2009). Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. *Energy Policy*, *37*(3), 1170–1179. doi.org/10.1016/j.enpol.2008.11.018.