Decentralized Energy Systems

A part of the global energy transition

Case study compilation

IEA Bioenergy: Task 32,36 & 44

November 2026



Inter-Task Project Decentralized Energy Systems

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Case study compilation

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Preface

This report illustrates examples of integrated energy solutions that combine different renewable technologies and provide valuable lessons learned for decision makers involved in energy transition.

The technologies and solutions presented in this compilation were selected due to their relevance in the field. However, IEA Bioenergy does not endorse any commercial products that may be mentioned in this report.

This report is a result of collaboration between IEA Bioenergy Task32 | Biomass Combustion; Task 36 | Material and Energy valorisation of waste in a Circular Economy and Task 44 | Flexible Bioenergy and System Integration. See Bioenergy | International Collaboration in Bioenergy for links to the work performed by IEA Bioenergy.

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Summary

Energy security, cost stability, climate responsibility and local resilience are no longer abstract policy goals; they are day-to-day operational realities for farms, business and communities across Europe. This report presents four case studies from Denmark, Germany and Sweden that have taken their energy futures into their own hands through locally integrated energy solutions.

The *Dairy farm in Lambrechtshagen in Germany* operates a 350 kWe / 600 kWth biogas combined heat and power (CHP) unit fueled mainly by on-farm manure and crop residues, generating around 2,800 MWh of electricity and 4,800 MWh of heat each year. A 250 kWp rooftop PV system adds a further 251 MWh, while the digestate returns to the fields as fertilizer, closing the nutrient loop. The result is roughly 2,5 t CO_2eq avoided annually and 160—224 thousand euros in yearly savings, in addition to revenue from surplus electricity sold under Germany's Renewable Energy Sources Act (EEG scheme), which provides financial support for renewable electricity fed into the grid.

The P*ig breeding farm in Panzow, Germany*, took a different route. The family replaced its old gas heating with a 200-kW wood chip boiler paired with a 7,700-litre thermal buffer tank and added a 43 kWp PV system generating about 90-100 thousand kWh per year. Together, these systems have eliminated fossil heating, provided around 300 MWh of heat per year, and reduced electricity costs while ensuring a reliable power supply for critical farm operations.

Vasen Farm (Vasen Lantbruk) in Sweden has established a decentralized biogas energy system that converts manure from its own dairy herd of more than 500 cows into renewable energy. The manure is supplied continuously throughout the year and digested anaerobically to produce biogas, which fuels a combine heat and power (CHP) unit generating 220 kW of electricity and 270 kW of heat. The system supplies the farm's energy needs and can operate in island mode during grid outages, enhancing energy security and production continuity.

These farms show what hybrid, farm-scale energy systems can look like in practice: not pilot projects, but proven technologies already paying for themselves through avoided costs, feed-in revenue, and a tighter nutrient loop.

The *Silkeborg* integrated heat pump and biomass *district heating plant in Denmark* case illustrates how a combination of technologies can increase overall efficiency. The biomass plant is specifically designed to utilize low-quality biomass like garden and park residues. The hybrid plant produces hot water that contributes to providing heating for around 55,000 consumers. The hybrid concept was developed to support Silkeborg Varme's transition to low-carbon heating solution. Using locally sourced biomass and combining biomass combustion with electricity-based heat generation helps stabilise heat prices by reducing dependence on fossil fuels and volatile electricity markets.

Despite the varied technological configurations of the projects, ranging from agricultural applications (Dairy, Pig breeding, and Vasen farm) to hybrid technical symbiosis concept (Silkeborg district heating plant), the analyses of flexibility alongside the decentralized energy focus revealed significant similarities, benefits, and key insights regarding flexibility.

A common feature across the projects is the flexibility of their energy output. Three out of four systems are designed to provide both electricity and heat. Heat is provided by all projects investigated for their own use or to supply a district heating network. In all cases, the use of flexibility leads to a reduction in operating costs. While all projects provide heat, two of the systems use flexibility to additionally produce fertilizers as a local resource. In the Vasen Farm, storing digestate for up to eight months allows for the application of nutrients at the right time during the growing season.

Flexibility arises through the intelligent connection of systems. The combination of PV with biomass and the coupling of heat pumps with biomass plants shows that flexibility can be significantly increased through technical

symbiosis. Also, the flexibility of the projects enables the creation of social value beyond pure energy generation. Local employment is supported, keeping economic value through operation, maintenance, and service on-site, thereby reducing financial outflows to external suppliers. Furthermore, it includes the strengthening of regional supply chains (e.g., local forest management) and the provision of valuable resources such as fertilizer. All systems reduce CO_2 emissions. Additionally, the local procurement of wood chips supports regional forestry, which helps to sequester carbon in the landscape.

Decentralized Energy Systems

BACKGROUND

Decentralized Energy Systems (DES) are energy systems that generate, convert, store, and supply energy locally using available resources. These systems are typically owned or operated by local energy consumers, communities, or businesses and may include a wide range of renewable and low-carbon technologies, such as solar PV systems, small wind turbines, biomass or biogas facilities, combined heat and power (CHP) plants, heat pumps, battery and thermal energy storage, as well as systems producing renewable gases, hydrogen, or liquid fuels. When interconnected, these technologies can form microgrids or local energy communities capable of operating both connected to the main grid and, in some cases, independently. While the concept of decentralized energy systems encompasses a broad range of energy vectors and technologies, the four case studies presented in this report focus specifically on decentralized electricity and heat generation systems.

The growing relevance of decentralized energy is key factor in global and regional energy transitions. According to the International Energy Agency[1], renewables in global electricity will rise from 34% in 2024 to 43% by 2030. At the European level, governments have set ambitious targets of 42,5% renewable energy in final consumption by 2030[1]. Current geopolitical instability and volatile energy markets are prompting many countries to reconsider their energy systems, with a growing focus on energy security and independence. This reinforces the importance of diversifying energy sources and maximizing the value of domestic resources.

What makes decentralized systems valuable beyond installed capacity? These systems can contribute to communities' self-sufficiency that centralized infrastructure can't provide[2]. Decentralized energy systems can also be flexible and integrated across sectors[3]. In other words, decentralized energy systems help to balance supply and demand, even when using sources like wind and solar power. At the same time, the stakeholders face challenges by integration into exiting grid infrastructure and regulatory compliance[4].

Digital technologies are helping this transition in practical terms. Peer-to-peer (P2P) energy trading platforms are one such tool. A study[5] found that implementing P2P electricity trading can reduce electricity costs by up to 20% and cover more than two-thirds of household and industrial electricity demand with nationally generated wind and solar power. These results suggest that P2P trading is very useful for communities to take a more active role in managing their own energy supply.

In agriculture, this topic matters because high energy demand meets abundant renewable resources: solar radiation, wind exposure, and organic waste create strong potential for on-farm power generation[6]. This pairing is a natural fit for the circular economy. Crop residues and manure, often a cost or environmental burden, become biogas feedstock, while the leftover digestate returns to the soil as bio-fertilizer, improving soil health

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[1] International Energy Agency. (2025). *Renewables 2025 - Analysis and forecasts to 2030*. www.iea.org

[2] Alanne, K., & Arto, S. (2004). Distributed energy generation and sustainable development. *Renewable & Sustainable Energy Reviews*, *10*(6), 539–558. https://doi.org/https://doi.org/10.1016/j.rser.2004.11.004

[3] Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable & Sustainable Energy Reviews*, (45), 785–807.

[4] Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., & D'haeseleer, W. (2005). Distributed generation: Definition, benefits and issues. *Energy Policy*, *33*(6), 787–798. https://doi.org/10.1016/j.enpol.2003.10.004

[5] dena. (2023). *The Decentralized Energy System in 2030*. www.dena.de

[6] Majeed, Y., Khan, M. U., Waseem, M., Zahid, U., Mahmood, F., Majeed, F., Sultan, M., & Raza, A. (2023). Renewable energy as an alternative source for energy management in agriculture. *Energy Reports*, (10), 344–359. https://doi.org/https://doi.org/10.1016/j.egyr.2023.06.032

and reducing the need for chemical inputs[7]. Farms that adopt this model step away from volatile fuel markets and gain real independence, generating their own energy while enabling exchange with the surrounding community. A similar mechanism can be observed at district heating plants when they move away from fossil fuels and choose a hybrid heat generation setup where they avoid moving from one volatile market (fossil fuels) to another (electricity). Introducing a biomass boiler that can use a locally or regionally sourced, storable solid biomass fuel, and more generally can operate on a solid biofuel market that is less volatile, also introduces a large degree of flexibility and independence that creates security of supply at limited cost.

HOW DECENTRAL AND HYBRID ENERGY SYSTEMS PROVIDE FLEXIBILITY

This section introduces the flexibility aspects explored in the case studies presented in this report. It begins by outlining key messages on flexibility in bioenergy systems and then highlights the specific characteristics and opportunities associated with decentralized energy systems. Later in the report, the four case studies are presented, and their main results are summarized and compared, highlighting different approaches to flexibility and the options they offer.

GENERAL FLEXIBILITY CONSIDERATIONS

The use of biomass and bioenergy can be improved through various forms of flexibility. IEA Bioenergy Task 44, *Flexibility and System Integration*, was launched in 2019 to develop a common definition of flexible bioenergy, which is defined as follows: *"Flexible bioenergy is defined as a bioenergy system that can provide multiple services and benefits to the energy system under varying operating conditions and/or loads. "*

In the following overview and text, we will outline seven important categories that contribute to this flexibility, providing examples and explanations for each.

Table 1. Flexibility options established by IEA Bioenergy Task 44 with examples.

Option/Category	Description	Example
Flexibility in renewable resource types	Which renewable energy sources are used in the system under consideration and how they are combined within a single operating scheme	Example: Combining biomass and PV in the system

[7] Doyeni, M. O., Stulpinaite, U., Baksinskaite, A., Suproniene, S., & Tilvikiene, V. (2021). The Effectiveness of Digestate Use for Fertilization in an Agricultural Cropping System. *Plants 2021, Vol. 10, Page 1734*, *10*(8), 1734. https://doi.org/10.3390/PLANTS10081734

Option/Category	Description	Example
Flexibility in energy inputs and outputs	Which types of renewable energy carriers (e.g. heat, electricity, hydrogen, bioenergy carriers or chemicals) are used as inputs and/or outputs in the system and how flexibly they can be applied	Example: Bioenergy plants designed to produce both electricity and heat
Flexibility in providing societally relevant services	Which societally relevant services (e.g. heating & cooling, electricity, mobility, industrial heat, chemical processes, circularity services or consumables) are provided and how flexibly these services can be delivered	Example: Biomethane is used as a dispatchable fuel for local buses or trucks
Integration across sites, networks and markets	How is the system integrated across locations, networks, and markets, including on-site use, cross-sector or community cooperation, local networks, national grids or transport, and opportunities for international trade	Example: Biomass-fired boiler provides flexible process steam for an industrial plant
Non-energy products	Non-energy products are made from biomass but not used for energy. Examples include biochar for soil improvement, biocarbon for materials or carbon storage, and fertilizers to support agricultural production	Example: Biogenic CO_2 from a bioenergy plant is supplied to a greenhouse
Time scale of temporal flexibility	How quickly can a system adjust operations, outputs, or resource use, ranging from sub-seconds and minutes to hours, days, months, or seasonal changes	Example: Biomass CHP shifting between higher electricity and higher heat production within a day

Option/Category	Description	Example
Other criteria	These are key system features affecting flexibility, such as minimum load, how quickly output can change, start-up time, and additional aspects like storage or other system-specific capabilities	Example: Heat from a Biomass plant is stored in a hot water system for later use

To comprehensively evaluate the flexibility of biomass utilization within an integrated energy system, several dimensions are employed to cover both material and energetic aspects. First, flexibility in resource types is considered. This category describes which renewable energy sources are utilized within the system and how they can be combined within a single operating scheme (e.g., the synergistic use of biomass alongside other renewable sources). Furthermore, flexibility in energy inputs and outputs examines which energy carriers—such as heat, electricity, hydrogen, or chemical carriers—serve as inputs or outputs and how flexibly their application can be managed (e.g., the flexible switching between electricity generation and heat supply to optimize system utilization). Another key aspect is flexibility in providing societally relevant services. This analyses which services, such as heating, mobility, or industrial processes, are provided and how flexibly these can be delivered (e.g., dynamically adjusting heat output to meet shifting industrial process requirements). The integration across sites, networks, and markets examines the connectivity of the system, including on-site use, cooperation within local networks, and integration into national grids or international markets (e.g., connecting a local biomass plant to the national grid to participate in frequency regulation markets). An additional category is the production of non-energy products. This involves the material utilization of biomass that is not primarily intended for energy production, such as the manufacturing of biochar for soil improvement, biocarbon for carbon storage, or fertilizers for agricultural production. The temporal category is captured by the time scale of temporal flexibility. This describes how quickly a system can adjust its operations or resource consumption, ranging from short-term load adjustments in minutes to seasonal cycles. Finally, other criteria are considered for specific technical features. These include parameters such as minimum load, start-up time, or the capacity for biomass storage, all of which fundamentally determine the system's operational flexibility.

SPECIAL ASPECTS OF DECENTRALIZED/HYBRID ENERGY SYSTEMS

In the introduction part of the report several aspects of the decentral/hybrid system are mentioned and addressed, specifically regarding how they can contribute to improving the energy system integration. However, these same aspects can be found within categories which describe flexible issues shown in Table 1. Table 2 displays both the decentralized energy system and flexibility characteristics, thereby highlighting similarities.

Table 2. Key aspects of decentralized biomass systems (left) and categories for assessing flexibility factors (IEA Bioenergy Task 44 definition) (right).

Decentralized System	Flexibility Category
Decentralization	Flexibility in renewable resource types (e.g. combining the use of renewables and biomass)

Decentralized System	Flexibility Category
Hybridization	Flexibility in energy inputs and outputs (e.g. producing both electricity and heat)
Energy Autarky	Integration across sites, networks, and markets (e.g. integrating bioenergy plants into existing energy grids)
Increased Energy Efficiency	Non-energy products category (e.g. producing fertilizers or animal feed from biomass)
Reduction of Greenhouse Gases	Flexibility in providing societally relevant services (e.g. biomethane used as fuel for buses or trucks)
Flexibility and Adaptability	Time scale of temporal flexibility (e.g. adjusting production to changing energy demands)
Cost Efficiency	Flexibility in renewable resource types (e.g. combining renewables and biomass to meet on-site electricity and heat demand)
Promotion of Local Economies	Flexibility in providing societally relevant services (e.g. production of fertilizer)

These findings are encouraging, as they indicate that decentralized systems already provide a high degree of flexibility while maintaining economic stability. Recent developments increasingly aim to further enhance this flexibility by contributing to grid security and providing additional flexible functions, such as energy storage and the use of different technical options across seasons and times of day.

PURPOSE OF THIS REPORT

This report illustrates examples of integrated energy solutions that combine different renewable technologies and provide valuable lessons learned for decisionmakers involved in energy transition. A short synthesis chapter on flexibility is also included in the conclusion, highlighting common strategies and key lessons across the four case studies. An overview of the four case studies is presented in Table 3. Although the paper's subtitle refers to decentralized energy systems as "A part of the global energy transition," the four case studies and the subsequent discussion focus geographically on Europe. Denmark, Germany, and Sweden are all EU countries that share similar incentives for decarbonization, similar energy infrastructure, and similar energy prices. A case

study in other parts of the world might yield different results and influence this European perspective as well as several of the conclusions.

Table 3. An overview of the four case studies.

Project/Company	Technology	Feedstock	Products/by-products (energy, materials)	Considerations
Dairy Farm (Germany)	Anaerobic digester (mesophilic, no O_2) + Biogas CHP unit (350 kWp elec. + 600 kWp heat) + PV system (stable roof, 250 kWp, daylight hours)	Cow manure (slurry & solid, year-round) + Crop residues (silage, straw: seasonal)	Biogas (60% CH_4 → CHP fuel), Electricity (on-farm use + grid feed-in), Heat (space heating & hot water), Digestate (organic fertilizer → fields)	Closed nutrient loop + Solar surplus
Pig breeding farm (Germany)	Wood chip boiler 200 kWp + Buffer tank + PV 43 kWp	Wood chips (local, storable)	Heat (distribution + stored), On-farm electricity, Grid exchange	Thermal buffering + Seasonal balancing
Vasen Farm (Sweden)	Anerobic digestor + biogas CHP unit	Cow manure	Biogas to 220 kW of electricity and 270 kW of heat	
Silkeborg hybrid district heating plant (Denmark)	22 MW Air-to-water heat pump + 20 MW biomass plant with a flue gas condenser from	Low-quality biomass: garden and park residues	Hot water contributes to provide heating for around 55,000 consumers	

CONTRIBUTIONS FROM PARTICIPATING IEA BIOENERGY TASKS

This report was developed through collaboration among several IEA Bioenergy Tasks, each contributing its specific expertise and perspective. The combined input enabled a comprehensive assessment of decentralized energy systems, covering technical, environmental, operational, and system integration aspects.

IEA Bioenergy Task 32 – Biomass Combustion contributed the case study of the Silkeborg hybrid district heating plant in Denmark.

IEA Bioenergy Task 36 – Material and Energy Valorisation of Waste in a Circular Economy contributed the case studies of Dairy Farm and a Pig Breeding Farm in Germany, as well as the Vasen Farm (Robusta Gården concept) in Sweden.

IEA Bioenergy Task 44 – Flexible Bioenergy and System Integration assessed the flexibility characteristics of all case studies, evaluating how bioenergy technologies can support the integration of variable renewable energy sources and contribute to more resilient energy systems.

All participating Tasks contributed to the development of the overall project concept, while the work was coordinated and led by IEA Bioenergy Task 36.

MATERIAL AND METHODS

In each case study, key factors influencing the system structure were examined, including feedstock availability, environmental considerations, technical specifications, policy aspects, and flexibility.

In evaluating the four case studies, this report refers to seven distinct categories of this flexibility. These classifications are also utilized to describe Best Practice examples and are listed and described in an *IEA Bioenergy publication*[8]. Furthermore, an additional chapter in this report summarizes results of the four cases, showing some highlights and future developments (see chapter *Flexibility Potential*).

[8] EA Bioenergy Task 44: Flexible Bioenergy and System Integration. *Best practice*. Link.

Case study 1: Dairy Farm - with Biogas CHP and PV, District Rostock, Germany

Dairy Farm is a family-run dairy farm in the District Rostock, Germany. The operation integrates a biogas-driven combined heat and power (CHP) unit with a solar photovoltaic (PV) array installed on the livestock housing. This hybrid configuration provides both thermal and electrical energy for the milking facilities, the on-site shop, and administrative offices.

Figure 1 illustrates how the farm applies its *decentralized* energy system. The farm load of around 400 kWp, supplied primarily from renewable generation. This system ensures the circular economy model at farm scale.

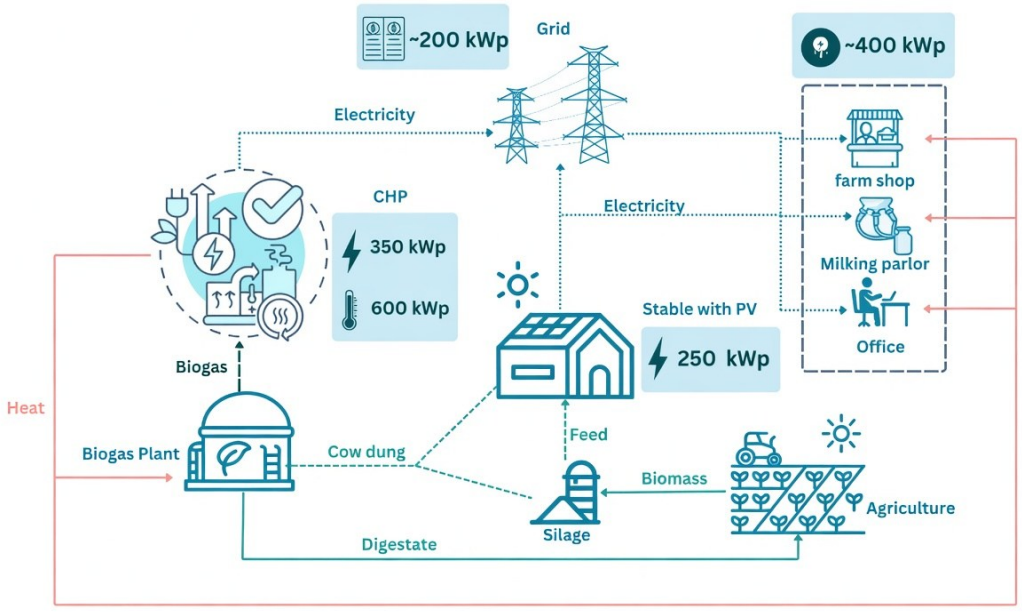


Figure 1. Hybrid energy system at Dairy Farm.

ABOUT THE FARM

Name of the plant/system: Dairy Farm.

Type of facility: Decentralized farm-based renewable energy system with biogas combined heat and power (CHP) as the operational energy module.

Owner/operator: Family-owned.

Location: Lambrechtshagen, District Rostock, Mecklenburg-Vorpommern, Germany.

Overview of input and outputs:

- Inputs: cow manure and crop residues (biogas plant feedstock), solar irradiation (PV).
- Outputs: electricity and heat for farm operation, digestate as organic fertilizer for farm fields.

Main flexibility aspects for this system/process/plant: The biogas CHP unit provides dispatchable baseload power that compensates for the intermittent output of the PV system, supplying electricity at night and during overcast conditions. Heat storage inherent in CHP operation provides temporal flexibility for heating demand. Surplus electricity can be fed into the public grid or sold in the future on P2P platforms.

History: *Dairy Farm* is a family-run dairy farm with farm shop and administrative office. The farm adopted decentralized renewable energy to reduce dependency on the external electricity grid, stabilize energy costs amid volatile fossil fuel markets, and make productive use of on-farm organic waste streams.

FEEDSTOCKS

The biogas plant at *Dairy Farm* is fed with farm organic residues including both liquid slurry and solid cattle manure from the dairy herd and crop residues like maize silage, straw, and other agricultural by products generated during crop production activities. The residues are transported to the biogas digester, requiring minimal to no pre-treatment prior to *digestion. Manure provides stable year-around supply, while crop residues introduce variability linked to harvest schedules, availability peaks in autumn and early winter following cereal and maize harvests. The CHP unit also requires a small quantity of fossil fuel (natural gas or diesel) for ignition and backup, but this could be negligible in proportion to the renewable feedstock. The PV system's feedstock is solar irradiation incident on the stable rooftop. Figure 2 shows* an overview of the Dairy Farm's feedstock.

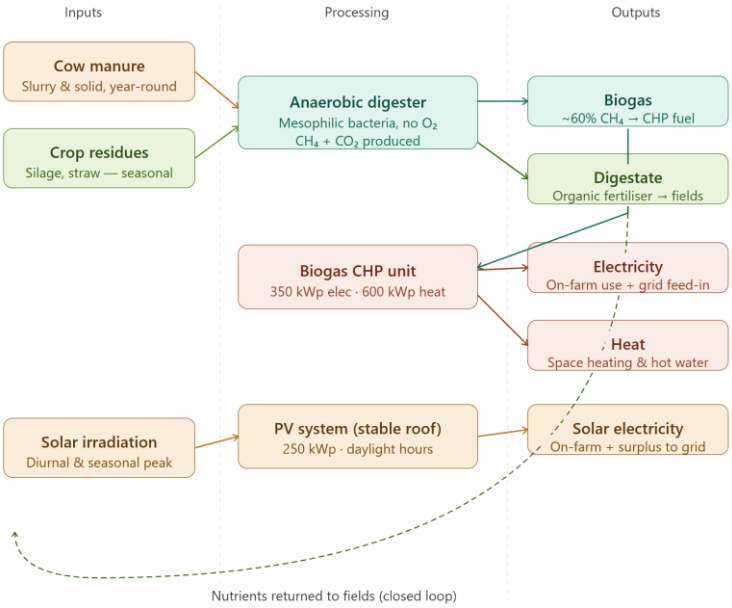


Figure 2. Dairy Farm feedstock.

PRODUCTS

Products obtained from the system: (1) Electricity – generated by the biogas CHP unit and the PV system; (2) Heat – produced by the CHP unit as a by-product of electricity generation; (3) Digestate – the semi-liquid residue remaining after anaerobic digestion; rich in plant-available nitrogen, phosphorus, and potassium.

In Germany, applying digestate as an organic fertilizer is a long-standing and legally regulated practice. The German Fertilizer Application Ordinance sets clear limits on nitrogen application rates and spreading conditions, keeping soil and water quality protected while giving farmers a stable framework to work within. In several countries, digestate is still classified as waste rather than a fertilizing product, which limits how it can be used on farmland and cuts into the economic value farms could otherwise capture from it.

Market opportunities: Electricity surplus is sold to the grid under the German public grid, providing a predictable revenue stream. Digestate has a local market as an organic fertilizer substitute, with economic value in reducing synthetic fertilizer purchases.

TECHNICAL DATA

The system components are:

1. Biogas anaerobic digester, continuously stirred tank reactor (CSTR), mesophilic operation (approximately 37°C),
2. CHP unit, internal combustion gas engine driving an alternator for electricity production, with heat recovery from engine cooling water and exhaust gases;
3. Rooftop PV array, monocrystalline or polycrystalline silicon panels on the cattle stable roof, connected to grid-tie inverters;
4. Heat distribution network, hot water piping connecting CHP thermal output to farm buildings;
5. Digestate storage and handling system.

The dynamic interaction between the two generation sources (PV and CHP) is illustrated in Figure 3, which shows simulated power output over one week in June, modelled using the REopt Web Tool[9]. The chart reveals a clear daily pattern: PV generation (yellow) rises during daylight hours, covering a significant share of farm electricity demand, while the CHP unit (red) operates continuously, stepping in to fill supply gaps during night-time hours and on days of low solar irradiation, most notably on 4 and5 June, when overcast conditions substantially reduced PV output. The grey area represents the residual demand met by grid imports, which remains modest throughout the week. No curtailed PV generation is recorded, indicating that on-site consumption and grid export absorb all generation efficiently.

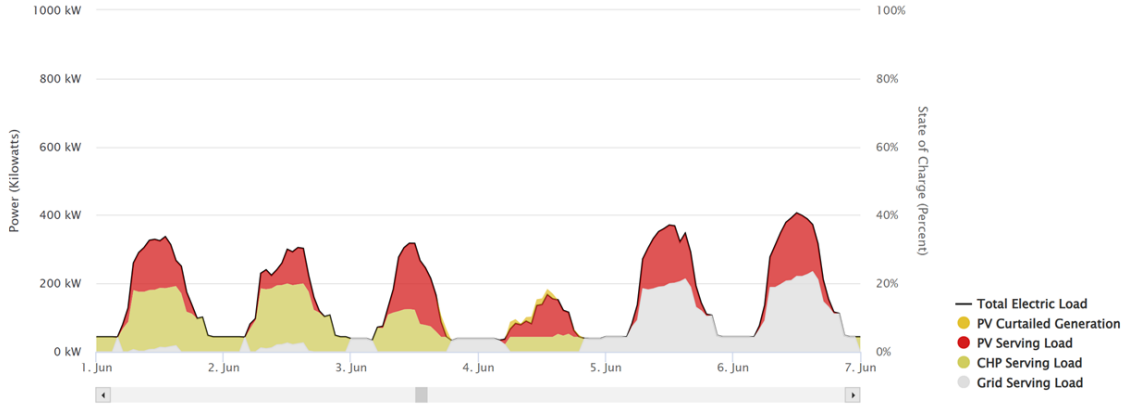


Figure 3. Simulated power (kW) for the PV and CHP plant over one week in June. Source: REopt Web Tool (Mishra et al., 2021).

Combining PV and CHP at Dairy Farm, the total annual on-site electrical generation amounts to approximately 3.051 MWh/year and total thermal generation to 4.800 MWh/year. The seasonal generation profile of the PV system, peaking in May–July and declining sharply in November–January, is directly complemented by the biogas CHP. This complementarity is the defining operational characteristic of the hybrid system at Dairy Farm.

[9] Mishra, S., Pohl, J., Laws, N., Cutler, D., Kwasnik, T., Becker, W., Zolan, A., Anderson, K., Olis, D., & Elgqvist, E. (2021). *Computational Framework for Behind-The-Meter DER Techno-Economic Modeling and Optimization-REopt Lite.*

ENVIRONMENTAL ASPECTS

The decentralized hybrid energy system implemented by this farm delivers reductions of greenhouse gases (GHG) towards several emission endpoints. The annual energy production, emission reductions towards greenhouse gas emission, displaced processes emissions (lateral movement as equivalent to Unloaded generator operation) and reduction in heat losses were calculated.

As the farm uses exclusively organic feedstocks from own farm, cow manure and crop residues produced on site, no external biomass transport emissions are irrelevant. This represents a material advantage over biogas systems relying on imported energy crops.

Together, the grid electricity displacement, the natural gas displacement and the avoided manure methane emissions quantified yield a combined gross GHG reduction of approximately 2,483 t CO_2eq/year, as summarized in *Table 4.*

Table 4. Estimated annual GHG reductions at Dairy Farm by emission pathway (indicative, based on literature emission factors).

Step	Emission pathway	Estimated (t CO_2eq/year)
Step 1	Grid electricity displacement (internal self-consumption only)	242.8
Step 2	Natural gas displacement (CHP thermal output)	Approx. 970
Step 3	Avoided manure methane emissions	1,270
Gross GHG Reduction		2,483

Beyond the quantified GHG reductions, the system delivers several co-benefits that carry environmental significance. Anaerobic digestion has been shown to reduce odour emissions from pig slurry by 70–80% compared to untreated slurry[10], while open slurry storage systems represent significant sources of ammonia, hydrogen sulphide, and other malodorous compounds that can cause nuisance to surrounding communities[11]. The closed nutrient cycle reduces the risk of nitrogen leaching into groundwater and local surface water bodies, relevant

[10] Pain, B. F., Misselbrook, T. H., Clarkson, C. R., & Rees, Y. J. (1990). Odour and Ammonia Emissions Following the Spreading of Anaerobically-Digested Pig Slurry on Grassland. Biological Wastes, 34, 259–267.

[11] Kupper, T., Häni, C., Neftel, A., Kincaid, C., Bühler, M., Amon, B., & Vanderzaag, A. (2020). https://doi.org/10.1016/j.agee.2020.10696

to an intensively farmed region[12].

Beyond the quantified GHG reductions, the system delivers several co-benefits that carry environmental significance. Anaerobic digestion has been shown to reduce odour emissions from pig slurry by 70–80% compared to untreated slurry[10], while open slurry storage systems represent significant sources of ammonia, hydrogen sulphide, and other malodorous compounds that can cause nuisance to surrounding communities[11]. The closed nutrient cycle reduces the risk of nitrogen leaching into groundwater and local surface water bodies, relevant to an intensively farmed region[13].

ECONOMIC ASPECTS

Biogas Upgrading (2026) indicates that European installation expenses for biogas CHP units generally fall between €1,200 and €2,000 per kilowatt of electrical capacity. Applying this range to the proposed 350 kWe unit results in an estimated investment of approximately €420,000 to €700,000 for the CHP system, including the engine-generator set and associated plant infrastructure. Based on prevailing German market rates for commercial rooftop solar, the PV installation is projected to cost between €225,000 and €325,000[14], influenced by specific components and site conditions. Thus, the total initial investment for the dual-source system is roughly €645,000 to €1,025,000, excluding any government incentives or low-interest loans. German renewable energy support programs, including KfW (Credit Institute for Reconstruction), Germany's public development bank, financing instruments and renewable energy incentive mechanisms, may further improve project economics by reducing financing costs.

The economic benefit of self-consumption is particularly significant because agricultural electricity prices in Germany have increased considerably in recent years. By generating its own electricity, Dairy Farm avoids purchasing 639 MWh from the grid, corresponding to annual savings of approximately €159,750 to €223,650.

Beyond self-consumption, exported electricity provides an additional revenue stream. Under current German market conditions, however, this revenue is increasingly shaped by competitive Renewable Energy sources ACT (EEG) auctions and wholesale electricity prices, which makes it more variable over time. For this reason, electricity export should be seen as a complementary income source rather than the primary driver of the project’s economic performance.

The economic attractiveness of the proposed system is primarily driven by three interconnected factors that work together in a practical and reinforcing way. First, the on-site generation of electricity significantly reduces the need to purchase energy from the grid, which translates directly into lower and more predictable operating costs for the farm. Second, any electricity that is not consumed internally can be exported to the public grid, creating an additional and stable revenue stream from surplus renewable generation. Ultimately, the setup provides benefits beyond power generation by reclaiming heat and nutrients from animal waste, converting a byproduct into an asset. Together, these factors shift the farm's financial profile from being energy-dependent to having a more robust and varied economic foundation.

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[12]Raimo, N., Vitolla, F., Esposito, B., Møller, H. B., Sørensen, P., Olesen, J. E., Petersen, S. O., Nyord, T., & Sommer, S. G. (2022). Academic Editors: Ornella Agricultural Biogas Production-Climate and Environmental Impacts. https://doi.org/10.3390/su14031849.

[13]Raimo, N., Vitolla, F., Esposito, B., Møller, H. B., Sørensen, P., Olesen, J. E., Petersen, S. O., Nyord, T., & Sommer, S. G. (2022). Academic Editors: Ornella Agricultural Biogas Production-Climate and Environmental Impacts. https://doi.rg/10.3390/su14031849.

[14] BDEW. (2026a). Gas Price Analysis – Households and Industry.

Table 5 presents a concise summary of the primary economic premises for the Dairy Farm hybrid system, detailing capital needs, expected energy costs, and the resulting annual income and cost reductions.

Table 5. Key economic parameters of Dairy Farm integrated bio and PV system.

Parameter	Unit	Range / Value
Capital Expenditure (CHP Biogas)	€	20,000 – 700,000
PV Installation Cost	€	225,000 – 325,000
Total Cost Investment	€	645,000 – 1,025,000
Farm electricity demand	MWh/year	639
Avoided electricity purchases	€/year	159,750 – 223,650

SOCIAL ASPECTS

At Dairy Farm, the integrated biogas system supports skilled local employment in operation, maintenance, and CHP servicing, activities that require on-site technical expertise. The closed feedstock model retains economic value within the local system and reduces financial outflows to external energy and fertilizer suppliers.

Through grid feed-in under the Renewable Energy sources ACT (EEG), the farm contributes to the regional energy mix of Rostock District. The EEG framework, which gave every energy producer the legal right to sell power to the grid, was designed precisely to position farms and rural communities as structural contributors to Germany's energy transition rather than passive consumers[15].

[15] Davidson, O. G. (2012, November). *German law gave ordinary citizens a stake in switch to clean energy*. Link.

POLICY ASPECTS

Dairy Farm operates within Germany's Energy Transition framework, supported by a set of established policy instruments that underpin the economic viability of its decentralized energy system.

The primary support mechanism is the EEG as previously mentioned, which guarantees a feed-in tariff for surplus electricity exported to the public grid. Since the 2017 reform, biogas plants with installed capacity above 150 kW must participate in the competitive auction mechanism, through which a feed-in premium is determined by competitive bidding[16]. The Renewable Energy Program (KfW 270) provides below-market-rate financing, reducing the cost of capital for farm-scale investments. The thermal output of the CHP may also be eligible for support under the Federal Funding for Efficient Buildings (BMWK, 2025). Tax depreciation allowances under the "Income Tax Act" further improve investment returns. Carbon Contracts for Difference (CCfDs), currently targeted at energy-intensive industry, are not directly applicable at farm scale, though future carbon market developments may open additional revenue streams for agricultural biogas operators[17].

This unified energy model supports Germany's national targets of reaching a 65% renewable energy share by 2030 and becoming climate-neutral by 2045[18]Regionally, Mecklenburg-Vorpommern's policies encourage localized renewable projects in the Rostock District, where this farm is situated. At the European level, the revised Renewable Energy Directive (RED III, 2023) and the REPowerEU plan reinforce the strategic relevance of integrated agri-energy systems of the type operated at Dairy farm.

FLEXIBILITY ASPECTS

Dairy farm demonstrates flexibility across various dimensions, combining renewable resource diversity, weather adaptability, grid integration, and circular economy co-products within a single farm-scale system.

Renewable resource flexibility is achieved through the complementary pairing of a dispatchable bioenergy source, the biogas CHP, which is fully controllable, with an intermittent renewable source, the rooftop PV array. PV covers daytime demand peaks while biogas CHP fills supply gaps during night-time hours and overcast conditions, ensuring near-continuous on-site renewable supply throughout the year. On the feedstock side, manure provides a continuous year substrate that moderates the seasonal variability introduced by crop residue availability, which peaks in autumn and early winter following cereal harvests.

Grid integration and market flexibility are enabled by the farm's bi-directional metering and EEG feed-in arrangement, which allows surplus electricity from both CHP and PV to be exported to the public grid. In future, participation in peer-to-peer (P2P) energy trading platforms would extend this to direct bilateral trading relationships with neighbouring farms and households, further monetizing the farm's flexibility and deepening its integration into the local energy community5. Non-energy products complete the flexibility scenario: digestate from the biogas process serves as an organic fertilizer whose application timing can be adjusted to match crop needs and field access conditions, adding agronomic flexibility to the system's circular economy contribution and reducing the farm's dependence on synthetic fertilizer supply chains.

By employing qualified local staff in the operation and maintenance of the combined heat and power plant, as well as through the closed-loop raw materials model within the local system and the reduction in financial outflows to external energy and fertilizer suppliers, the plant is well integrated both socially and locally and is

[16] Federal Ministry for Economic Affairs and Energy. (2017). *Renewable Energy Sources Act*.

[17] Federal Ministry for Economic Affairs and Climate Action (BMWK). (2025). *Directive on the funding of climate-neutral production processes in industry through Carbon Contracts for Difference*.

[18] German Federal Government. (2021). *Federal Climate Change Act*. Link.

therefore also flexible in terms of changing conditions.

FUTURE DEVELOPMENT

From the perspective of Dairy farm as an operating farm, the most immediate development opportunity is the addition of electrical battery storage. The Mishra study[9] confirms that a battery system would allow the farm to capture surplus PV generation during peak solar hours and redeploy it during the evening, at night, or on overcast days, directly reducing grid imports and lowering electricity costs. This upgrade would not require changes to the existing CHP or PV infrastructure and represents a natural next step in the farm's energy self-sufficiency journey.

In terms of capacity build-out, the farm has potential to expand the rooftop PV system to cover additional stable and storage building surfaces, increasing total on-site renewable generation and further reducing grid dependency. An assessment of available roof area and structural suitability would be the logical first step. The biogas facility could be enhanced in the future with upgrading technology to create biomethane. This could be fed into the national gas network or used for transportation, creating new income sources beyond heat and power.

Future opportunities may also arise from peer-to-peer local energy trading schemes, which are still evolving within the European electricity market and depend on further regulatory development.

Regarding integration, applying P2P energy trading platforms, as outlined in the DENA 2030 decentralized energy market concept[5], represents a medium-term opportunity for the farm to trade surplus electricity directly with neighbouring farms and households, generating additional income and strengthening the local energy community.

CONCLUSIONS/RECOMMENDATIONS

This system can be considered decentralized because generation, storage, and consumption all take place within a single farm boundary using locally available resources. This approach minimizes energy loss during transport, retains economic benefits locally, and matches power generation with actual farm needs. Consequently, the farm functions as a food producer, an energy provider, and a nutrient reclaimer, showcasing a multi-purpose model that enhances rural sustainability and energy security.

In summary, this farm serves as a functional template for reducing agricultural carbon footprints through combined bioenergy and solar systems, offering valuable data for farmers, energy experts, and regional planners.

DAIRY FARM PHOTOGRAPHS

The following images show the farm's energy production system. The biogas reactors (*Figure 6*) and the biowaste feeder (*Figure 4*) demonstrate the property's commitment to energy recovery from waste, turning what would otherwise be discarded into a renewable resource.



Figure 4. Biowaste Feeder



Figure 5. Manure pump



Figure 6. Biogas Reactors

Case Study 2: Pig Breeding Farm with Wood Chip Heating and PV, Panzow, Germany

This case study features a family-run pig breeding farm in Panzow, District Rostock, Germany. What makes this Pig breeding farm distinctive is that the farm demonstrates that decentralized renewable energy is not limited to biogas systems. Solid biomass (wood chips) can replace fossil fuel heating while rooftop PV substantially reduces grid electricity purchases. The operation replaced its gas-based heating with a wood chip boiler that heats livestock areas, housing, and storage, using a buffer tank for operational flexibility. Decoupling the boiler operation from instantaneous heat demand enables more efficient biomass combustion. This combined biomass and solar strategy removes fossil fuel reliance, lowers costs, and supports climate goals. As shown in Figure 7 the farm operates as a commercially mature (TRL 9) and directly replicable decentralized energy model for pig and poultry farming across Northern and Central Europe.

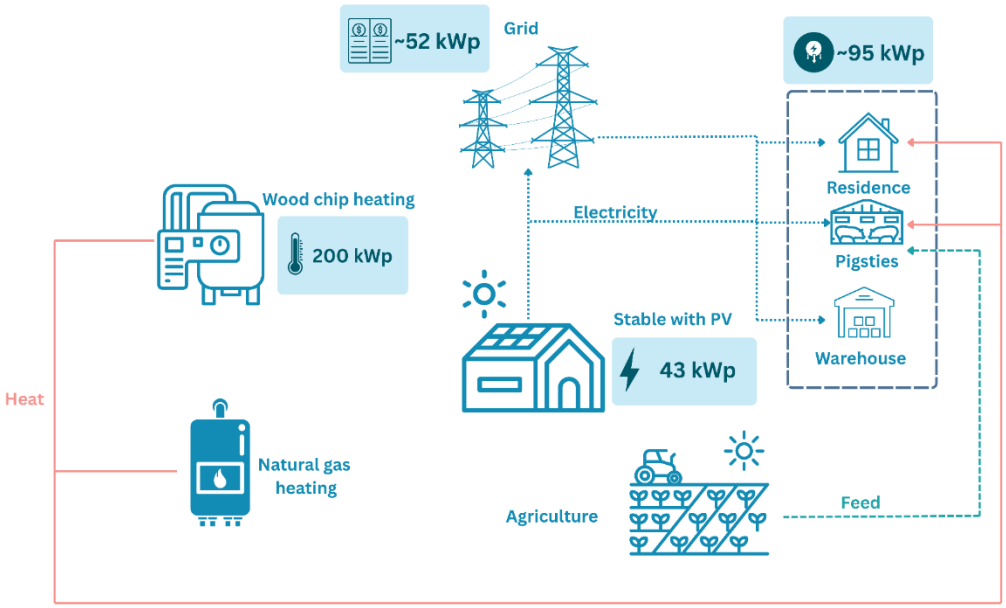


Figure 7. Case Study 2 - Hybrid energy system in Pig Breeding Farm.

ABOUT THE PLANT/SYSTEM

Type of facility: Pig breeding farm (pigsties, residential buildings, storage warehouse).

Location: District Rostock, Mecklenburg-Vorpommern, Germany.

Overview of inputs and outputs:

- Inputs: wood chips (biomass boiler feedstock), solar irradiation (PV).
- Outputs: heat for pigsties, residential buildings and warehouse; electricity for exhaust ventilation, lighting, and water pumps.

Main flexibility aspects: The wood chip boiler provides continuous, weather-independent thermal energy; the buffer tank decouples heat production from instantaneous demand (temporal flexibility over hours to days). The PV system offsets electricity during daylight hours. Future upgrades identified in simulation include battery storage (to capture surplus PV) and smart load management (to align ventilation and pump operation with PV peaks).

History: The farm was founded in 1995 and started in 2022 to replace natural gas heating with a wood chip

boiler to reduce fossil fuel dependency, cut operating costs in response to volatile gas prices, and utilize locally available renewable biomass from the surrounding rural landscape. The PV system was subsequently added to offset electricity consumption by the electrically driven systems essential to animal welfare, exhaust ventilation, water pumps, and lighting, which must operate reliably regardless of grid conditions.

FEEDSTOCKS

The biomass boiler at the Pig breeding farm is fuelled by wood chips sourced locally from the surrounding Mecklenburg-Vorpommern region, which has significant forest cover and an active wood supply sector. Wood chips are storable, transportable solid biomass fuel, unlike biogas, making fuel inventory management straightforward, the farm can maintain a stockpile to buffer against short-term supply disruptions or seasonal variation in delivery logistics. No significant pre-treatment is required beyond standard chipping and drying at the supply source. The boiler feed system handles size-classified chips automatically via a screw conveyor. Wood chip logistics fluctuate, with supply usually managed in the colder months. Solar output follows the opposite trend, peaking in summer, which is balanced by importing grid power in winter and exporting surpluses in summer. Figure 8 shows an overview of the feedstock Pig breeding farm.

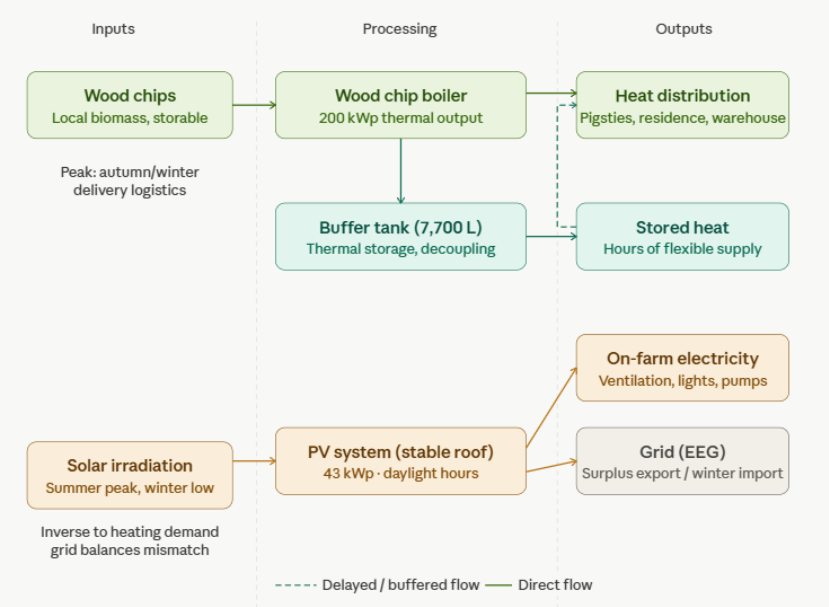


Figure 8. Pig breeding farm feedstock.

PRODUCTS

Products obtained:

1. Heat – produced by the wood chip biomass boiler.
2. Electricity – generated by the rooftop PV system.

Market opportunities: The primary economic benefit is cost savings from the elimination of natural gas purchases for heating. Surplus PV electricity may be sold to the grid under EEG feed-in tariff provisions. Local biomass procurement supports the regional wood supply chain and contributes to the circular economy of the Mecklenburg-Vorpommern rural economy.

TECHNICAL DATA

The energy system at Pig breeding farm consists of three integrated components: (1) a wood chip biomass boiler serving all thermal demand, (2) a rooftop PV array generating on-site electricity, and (3) a hot-water buffer tank providing thermal storage. The boiler replaced a natural gas heating system, eliminating the facility's dependence on fossil fuel dependency for heating. The PV system was added to reduce grid electricity purchases for the farm's most critical electrical loads. The two renewable systems operate independently but share the farm's electrical distribution infrastructure.

Technology used:

1. Wood chip biomass boiler – automatic feed system (screw conveyor), hot-water output, modulating burner.
2. A pressurized hot-water buffer tank – providing thermal inertia and enabling boiler operation at optimal load.
3. Hot-water distribution network – connecting boiler and buffer tank to pigsties, residential buildings, and warehouse via insulated pipework.
4. Rooftop PV array – monocrystalline or polycrystalline silicon modules on farm buildings, connected via grid-tie inverter.
5. Grid connection meter – for both surplus PV export and grid import.

Main innovation: at this Pig breeding farm lies not in developing new technologies, but in successfully replacing a fossil fuel heating system with renewable biomass and on-site solar power using commercially available technologies at a full farm scale. A properly sized thermal buffer tank helps to improve system efficiency and operational reliability.

Key technical challenge: reliable year-round wood chip supply of consistent quality (moisture content, chip size), particularly during prolonged cold spells with high heating demand. Secondary challenge: sizing the PV system and future battery storage to maximize self-consumption while managing seasonal surplus and deficit periods.

ENVIRONMENTAL ASPECTS

The decentralized energy system at Pig breeding farm delivers quantifiable greenhouse gas (GHG) reductions through two complementary pathways: the replacement of natural gas heating with renewable wood chip biomass, and the displacement of grid electricity through on-site solar PV generation. The data in Table 4 shows results of an analysis calculating annual energy production from installed system specifications, applying established emission displacement factors, quantifying avoided upstream emissions, and deducting operational losses.

The Pig breeding farm system is estimated to deliver a net GHG reduction of approximately 68.1 – 77.1 tCO_2eq/year, as summarized in *Table 6*. This is a more modest figure than Dairy farm, reflecting the absence of a manure methane pathway and the smaller scale of the PV system. It is, however, entirely consistent with the system's design intent: the complete elimination of fossil fuel heating on a working pig breeding farm, delivered through proven technology with no experimental components.

Table 6. Estimated net annual GHG reductions at Pig breeding farm, calculated using a four-step system boundary approach. Thermal energy production is estimated from documented boiler output and operating hours consistent with pig farming demand profiles in northern Germany. PV electricity offset is based on documented system performance.

Emission pathway	Estimated (t CO_2eq/year)
Natural gas heating displacement	60.6
Grid electricity displacement (PV)	11.4
Avoided upstream fossil fuel emissions	7.5 – 16.5
Gross GHG Reduction (Net Total)	79.5 – 88,5
Emission pathway	Estimated (t CO_2eq/year)

By switching away from natural gas, the farm also eliminates the risk of methane leaking during gas extraction and distribution, an issue that is increasingly under the spotlight as the EU tightens its methane regulations[19]. On top of that, sourcing wood chips locally supports forest management activities in Mecklenburg-Vorpommern, such as thinning and residue collection, which in turn benefits regional employment and helps keep carbon locked in the landscape.

The buffer tank performs a subtle yet vital function: it allows the boiler to operate at a consistent, high-efficiency rate. This prevents energy waste and increased emissions caused by frequent on/off cycling and the resulting incomplete combustion. Meanwhile, the rooftop PV system provides clean electricity for around 25–30 years, and panels have been shown to pay back their manufacturing energy within 1.7–2.7 years under Southern European conditions, a figure likely closer to 3–4 years at Pig breeding farm's latitude, though still well within the system's operational lifetime[20]

Finally, the ash left over from burning wood chips does not have to go to waste. When spread on farmland, it can act as a natural lime and potassium supplement.

[19] European Commission. (2020). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*. Link.

[20] Fthenakis, V. M., & Kim, H. C. (2011). Photovoltaics: Life-cycle analyses. *Solar Energy*, *85*(8), 1609–1628. https://doi.org/10.1016/j.solener.2009.10.002

ECONOMIC ASPECTS

The energy system at Pig breeding farm exemplifies a robust and low-risk economic model, built on mature, widely deployed technologies in Germany.

According to the Market Overview of Wood Chip Heating Systems by the Agency for Renewable Resources (FNR), the capital investment required for wood chip heating systems is heavily influenced by economies of scale, as the system capacity grows, the cost per kilowatt tends to decrease. For a 200-kW installation the total investment must account for more than just the boiler itself. This implementation requires a detailed technical framework, including automated fuel management, advanced combustion regulation, and specialized storage facilities. Therefore, initial capital investments for such initiatives usually range from €120,000 to €180,000 FNR, 2017). These costs are subject to variation based on the site's existing infrastructure, the complexity of the heat distribution grid, and specific environmental standards for emissions.

The project's economic viability is strengthened by its eligibility for the (BEG) subsidy program, which provides a maximum grant of €15,000 per project. The economic advantage of biomass heating remains substantial, based on a local sourcing price for wood chips (3-4 cm3) ranging from €4 to €9 per cubic meter (m3), the equivalent fuel cost translates to approximately €0.005 to €0.014 per kWh of thermal energy. Comparatively, current natural gas prices for German agricultural and commercial users typically sit between €0.08 and €0.12 per kWh (BDEW, 2026). Given an estimated yearly heat production of 300 MWh, the system is forecast to provide net annual fuel cost reductions between €19,800 and €34,500.

The PV component adds a further layer of economic resilience. With installation costs between €900 and €1.600 per kWp (Kost et al., 2024), the 43 kWp system requires an investment of €38.700 to €68.800. At agricultural electricity prices of €0.25–0.35 per kWh[21],the system reduces grid purchases by €10.750 to €15.050 annually. Together, the integrated system delivers significant cost savings, reduces dependency on external energy markets, and demonstrates a sustainable, economically viable pathway toward energy independence, fully aligned with Germany's climate neutrality goals and the broader European energy transition.

Table 7 provides a summary of the project's key economic parameters, including capital expenditure, operational costs, and the annual savings generated by this integrated approach.

Table 7. Key economic parameters of Pig breeding farm's integrated biomass and PV system.

Parameter	Unit	Range / Value
Capital Expenditure (Biomass)	€	120,000 – 180,000
BEG Subsidy (Biomass)	€	15,000 (max)

[21] BDEW. (2026b, April 15). *Electricity Price Trends in Germany for Households and Industry*. Link.

Parameter	Unit	Range / Value
Annual Fuel Cost Savings	€	19,800 – 34,500
PV Installation Cost	€	38,700 – 68,800
Agricultural Electricity Price	€/kWh	0.25 – 0.35
Annual Grid Purchase Savings (PV)	€	10,750 – 15,050

SOCIAL ASPECTS

By replacing natural gas with locally sourced wood chips and generating on-site solar electricity, Pig breeding farm has decoupled its energy costs from fossil fuel markets, reducing exposure to price volatility and strengthening the long-term financial resilience of the family business. Additionally, avoiding grid disruptions improves animal welfare while also reducing financial and reputational risks linked to mortality events or regulatory violations. The decentralized farm-based energy systems increase resilience in agricultural supply chains and reduce systemic vulnerability in food production.

The sourcing of wood chips within Mecklenburg-Vorpommern generates socioeconomic benefits beyond the farm. The state has approximately 582,000 hectares of forest cover[22], supporting a timber and wood-processing sector. Demand for wood chips as an energy carrier contributes to the viability of forest management activities such as thinning, residue harvesting, and chipping, which in turn sustain rural employment in harvesting, logistics, and supply chains. Unlike spending on natural gas, which largely flows out through global energy markets, expenditure on wood chips tends to remain within the regional economy, supporting local income, employment, and tax generation[23]. This aligns with the Mecklenburg-Vorpommern state government's strategy of promoting regional biomass use for renewable energy production[24].

This farm operates where agricultural enterprises are key economic actors and energy consumers. On-farm renewable systems contribute to local energy transition goals and reduce pressure on regional distribution infrastructure. The farm's model, commercially mature, policy-supported, and based on locally available resources, demonstrates practical applicability for neighbouring livestock farms considering similar transitions.

[22] Bundeswaldinventur – National Forest Inventory, 2022. [The forest in Germany: Selected results of the fourth National Forest Inventory]. https://www.bmel.de/publikationen

[23] FAO. (2010). *Bioenergy and Food Security*. http://www.fao.org

[24] Ministry for Economic Affairs, I. T. and L. (2014). *Bioenergy*.
https://www.regierungmv.de/Landesregierung/wm/Energie/Biomasse/

POLICY ASPECTS

Pig breeding farm's energy system is fully aligned with Germany's Energy Transition framework and the national target of achieving climate neutrality by 2045. The replacement of fossil fuel heating with certified sustainable biomass is supported by the German biomass heating grant program (BEG), administered by BAFA, which provides investment subsidies for biomass boiler installations meeting efficiency and fuel quality standards. The EEG (Renewable Energy Sources Act) provides feed-in tariff income for surplus PV electricity. At the state level, Mecklenburg-Vorpommern's rural development and energy transition policies actively promote the integration of decentralized renewable energy systems in agricultural contexts, particularly using locally available biomass and on-farm generation. This strategy fits perfectly into the larger picture of European policy. For example, the EU Farm to Fork Strategy19 pushes hard for lower greenhouse gas emissions in food production and wants to see renewable energy used much more aggressively throughout agricultural supply chains. In Germany, these developments are supported by established regulatory frameworks governing agricultural energy installations, which provide standardized permitting pathways for biogas, biomass, and photovoltaic systems in rural areas, enabling implementation within clearly defined legal and technical requirements.

FLEXIBILITY ASPECTS

The system operates flexibly by utilizing renewable resources, adapting to weather conditions, being controlled by a buffer storage tank, and integrating with the grid.

Wood chips can be stored and used as and when required; unlike solar panels, they are not dependent on the weather or the time of day but are available all year round. This makes biomass a far more reliable resource for meeting the constant heating requirements of a farm. In this case, it is also a local resource; the local sourcing of biomass supports the regional timber supply chain and contributes to the circular economy in the rural economy of Mecklenburg-Vorpommern. The rooftop photovoltaic system plays an important role in reducing dependence on the electricity grid. The additional buffer storage decouples heat generation from current demand (offering temporal flexibility ranging from hours to days). The PV system balances electricity consumption during daylight hours.

Future expansions involving battery storage and smart load management would further increase the self-consumption of solar power and reduce peak load charges. In terms of the overall flexibility of integration into networks and the market, decentralized agricultural energy systems enhance the resilience of agricultural supply chains and reduce systemic vulnerability in food production. This is also an important safety factor.

FUTURE DEVELOPMENT

Three key improvements have been identified for Pig breeding farm:

1. Battery storage installation: a battery system would enable the farm to store excess PV electricity generated during peak solar hours (midday, summer months) and use it during the evening, overnight, or on overcast days, increasing solar self-consumption, reducing grid dependency for critical loads (ventilation, pumps), and improving supply resilience for animal-welfare-critical systems.
2. Smart load management: better intelligent control of the farm's highest-consuming electrical devices, exhaust ventilation fans, water pumps, and lighting, would align their operation with periods of peak PV generation, further increasing solar self-consumption and reducing peak demand from the grid. This approach is incredibly valuable for ventilation systems. Because these fans can be adjusted slightly without compromising safety, they offer some built-in operational flexibility. Since ventilation accounts for such a huge chunk of a farm's electricity bill, that flexibility really pays off.
3. Scaling up the PV system: If the farm adds more solar capacity, it could cover a much bigger portion of its yearly power needs right on-site. This is a direct route to lower bills and less exposure to volatile grid prices.

CONCLUSIONS/RECOMMENDATIONS

Pig breeding farm demonstrates that decentralized renewable energy for livestock farms does not require biogas or complex waste-to-energy systems, a combination of commercially available wood chip heating and rooftop PV is sufficient to achieve near-complete elimination of fossil fuel heating and substantial reduction in grid electricity consumption. All energy is generated on-site or sourced from local biomass supply chains, without dependence on centralized fossil fuel infrastructure. The economic and operational benefits are substantial: lower and more stable heating costs, reduced grid electricity bills, improved energy security, and enhanced animal welfare through reliable on-site energy supply.

The system is highly replicable: wood chip boilers and agricultural PV installations are commercially available, well-understood technologies with mature supply chains and installation expertise across Germany and Northern/Central Europe. The main barriers, upfront capital cost and access to local biomass supply, are manageable through existing German policy support instruments (BAFA biomass grants, KfW financing, EEG feed-in tariff). The wood chip boiler + PV model is directly applicable to any pig, poultry, or other livestock farm with a significant year-round thermal demand and adequate roof area for PV, making it one of the most broadly replicable decentralized energy models in European agriculture.

PHOTOS – PIG BREEDING FARM

The images show details of Pig breeding farm. Figure 9 shows the wood chip boiler, paired with a large thermal storage tank (Figure 11**Fehler! Verweisquelle konnte nicht gefunden werden.**) that helps the farm make the most of the heat it generates. The wood chips are crushed through an automated feeding system (Figure 10) and stored on-site in a dedicated storage area (Figure 13), ensuring a steady and locally sourced fuel supply. Figure 12 captures the rooftop of the stables fitted with photovoltaic panels.



Figure 9. Wood Chip Boiler

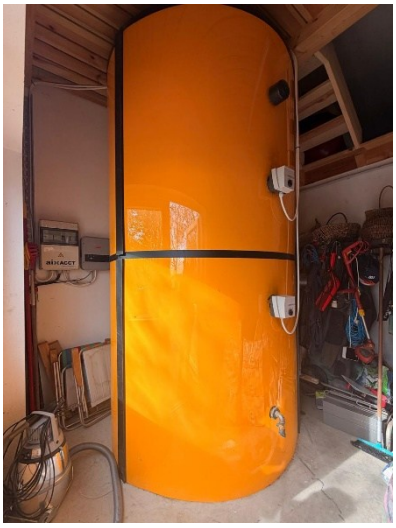


Figure 11. Thermal Storage Tank



Figure 10 . Wood chips crushed



Figure 12. Solar panels on the stables



Figure 13. Wood Chips Storage

Case study 3: Robusta Gården Concept. Pilot: Vasen Farm, Sweden

ABOUT ROBUSTA GÅRDEN CONCEPT

Robusta Gården[25] is a concept for decentralized, farm-based renewable energy systems. It was developed to explore how farms can sustain themselves when external energy and supply fall short. The concept combines the use of renewable carriers to produce electricity, heat and cooling, while integrating anaerobic digestion, CHP generation, and circular nutrient management into a cohesive system. Using locally available biomass — primarily manure, agricultural residues and forest biomass — these systems generate renewable electricity and heat, as well as digestate for use as organic fertilizer.

The system can be described as a flow from resource to end use product (*Figure 14*). The entire system is analyzed within a defined system boundary, typically corresponding to the farm or property, but potentially extending to a municipality, region, or national level depending on the scope of analysis. This boundary defines the limits within which resources, flows, and system performance are assessed.

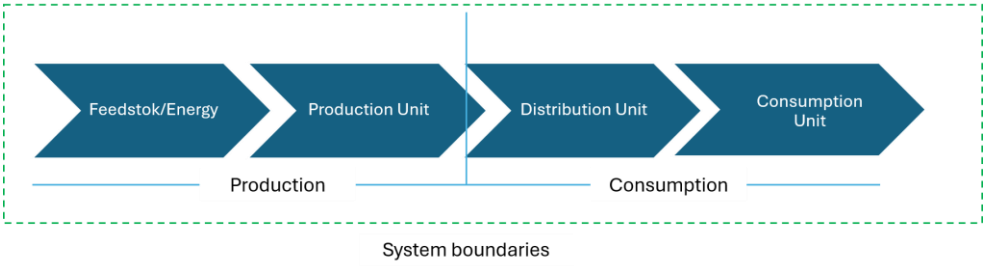


Figure 14. Robusta Gården system principle.

The Robusta Gården concept integrates renewable energy generation directly within agricultural operations and local resource cycles. A distinctive first step is the energy inventory – a structured assessment of locally available biomass resources at farm, property, or regional level – which determines system design and technology selection for each specific location.

FACTS ABOUT THE ROBUSTA GÅRDEN CONCEPT

- A local energy resource assessment is the critical first step in system development.
- Potential feedstocks include agricultural residues, livestock manure, forest biomass, and other organic by-products from farming and forestry operations. Feedstock availability varies seasonally.
- The energy inventory ensures each installation is precisely matched to its local resource base and determines the size of the system.

[25] Robusta Gården® is a registered trademark (Swedish Intellectual Property Office, reg. no. 624780).

- Modular integration of AD, CHP, renewable energy generation, and nutrient recycling at farm scale, with expansion determined by locally available biomass resources.
- The system can operate both island-mode and connected to local, regional, and national electricity distribution networks. Heat integration with farm buildings and potential district heat connection is included in system design.
- Temporal flexibility: The energy system combines intermittent (solar and wind) and dispatchable (biogas, CHP) generation technologies. The complementary operating profiles, together with energy storage, allow production to be scheduled in response to local energy demand and grid conditions.
- Storage: Balancing production and consumption over time rests on both planned production and storage. Energy stores in the forms of a property's resources allow biogas in gas holders for short-term dispatch; wood chips and other solid biomass as a longer-term fuel reserve; heat in thermal accumulators; and electricity in batteries.
- Implementation involves ongoing dialogue with municipal planning authorities, county administrative boards, and regional energy agencies. Permitting requirements follow Swedish/national environmental regulations for biogas plants; experience from operational sites has streamlined approval processes for subsequent installations.

Robusta Gården modular design allows adaptation to individual farms or regional multi-farm clusters, making it replicable across diverse agricultural contexts. Robusta Gården embodies the subsidiarity principle – the idea that energy, food and resource decisions should be made and value created at the lowest effective level, closest to where resources originate, and people live.

- Farmers and local stakeholders are involved in system design and governance from the outset.
- The concept supports local energy production and nutrient recycling while reducing dependence on external energy and fertilizer inputs. Multi-farm configurations can enable shared infrastructure and resource utilization.
- Applicable support instruments in Sweden: Klimatklivet (Swedish Environmental Protection Agency) – investment grant with dedicated application round for farm-based biogas to electricity and heat; Gödselgaspremien (Swedish Energy Agency) – production support for manure-based biogas; Kraftlyftet (Swedish Energy Agency) – investment support for measures strengthening the electricity system; tax incentive for biogas and biogasol (EU-approved October 2024, applicable from March 2025); EU RED III sustainability framework; potential future support for biomethane under REPowerEU.
- In a Swedish context, the concept is directly aligned with Sweden's national climate neutrality targets (2045), the national Bioeconomy Strategy, the national Food Strategy 2.0 (2025), and regional energy transition plans. At EU level, it supports REPowerEU biomethane targets and Farm to Fork circular agriculture objectives. Regional energy agencies in several Swedish counties have identified farm-based biogas as a priority deployment area.

Next steps: The concept was demonstrated at Vasen Farm (next section) and the current work focuses on replication, standardized site assessment, and financing and partnership models to support deployment at additional locations. In addition, next steps are planned in **(i)** structured scale-up to multiple farm-level installations; (ii)further development of farm products through new consumption units adapted to local agricultural and community needs creating local and regional value chains; (iii) development of local (municipal)

and regional cluster configurations; (iv) development of transport fuel with a focus on local and regional vehicle fleets, and (v) integration of digital tools for system performance monitoring.
Beyond digestate and electricity/heat, the modular concept enables further consumption units adapted to local agricultural and community needs. Surplus energy, beyond on-site consumption, can be distributed in response to consumption demand.

ABOUT THE PILOT OPERATING PLANT/SYSTEM

Name of the plant/system: Vasen Farm (Vasen Landtbruk).

Type of facility: Decentralized farm-based renewable energy system with biogas CHP.

Owner/operator: Vasen Farm, family owned.

Location: Nye, Jönköping County, Sweden

Overview of inputs and outputs:

3. Inputs: Manure from the farm's own herd used as biogas feedstock.
4. Outputs: Renewable electricity and heat and digestate (organic fertilizer).

Capacity: The installation provides 220 kW electrical and 270 kW thermal output, dimensioned according to the farm's available manure feedstock.

Main flexibility aspects: The installation offers flexibility on two timescales. In the short term, biogas storage lets the CHP unit adjust its output (hours to days) to match the farm's demand, providing plannable, dispatchable energy. Over the longer term, digestate storage of up to eight months allows nutrients to be applied at the optimal time during the growing season. Together, these give the farm both energy and agronomic flexibility.

History: The origin of the Robusta Gården concept traces back to the storms Gudrun (2005) and Per (2007), which affected southern Sweden, including Jönköping County. During these events, the farm experienced disruptions to transport access and deliveries of fuel and animal feed. This experience of vulnerability planted the idea of a self-reliant, resilient farm, driven by the goal of security of supply and operational resilience. Prior to installation Vasen Farm relied entirely on grid electricity, including heating hot water for the stables. Following installation, the farm went from full grid dependency to producing more than seven times its previous energy consumption — covering its own electricity and heat entirely from on-site renewable resources.

Investment: Vasen's installation was financed through farm equity and public support instruments, Klimatklivet (Swedish Environmental Protection Agency).

> Vasen Farm in Sweden has built and commissioned a biogas plant with electricity generation capable of island-mode capability, transforming the farm from an energy consumer into covering its own power needs. With the ability to keep running during grid disruptions, the farm can maintain production and ensure reliable food supply and animal welfare—even during prolonged power outages.

FEEDSTOCKS

The biogas facility is fed with manure from the farm's own dairy herd of more than 500 cows, providing a continuous, year-round feedstock supply collected on-site. As the animals produce manure consistently throughout the year, there is no seasonal variation in feedstock availability. The manure comes solely from the farm's own herd and requires no special pre-treatment; it originates from deep-litter bedding and is fed continuously to the digester. This single feedstock stream is sufficient to sustain year-round biogas production.

PRODUCTS

Energy products (primary): Renewable electricity and heat from biogas CHP — 220 kW electrical and 270 kW thermal — covering the farm's own energy needs.

Non-energy products: Digestate: nutrient-rich organic fertilizer reused within the agricultural system, replacing synthetic inputs.

Market opportunities: On-site energy consumption (primary), local grid feed-in (electricity), and local/regional market for digestate as organic fertilizer. Growing policy support for renewable energy and organic farming strengthens market outlook.

TECHNICAL DATA

The farm converts manure from its own herd into biogas to fuel a combined heat and power (CHP), unit providing electricity and heat for farm. Surplus electricity is exported to the grid, while digestate is returned to the fields as fertilizer.

Technology used (components): (1) Feedstock handling – mixer wagon for mixing and loading manure from deep-litter bedding, with no special pre-treatment; (2) Anaerobic digester with integrated gas storage and a post-digester; (3) CHP unit – gas engine with black-start and island-mode capability; (4) Heat distribution – insulated PEX culvert with heat exchangers; (5) Electricity distribution – transformer and switchboard; (6) Digestate storage – the farm's former manure tank. The consumption units – barn, residence, irrigation, and calf barn – use the farm's existing equipment, connected to the new energy source.

Technical data: The CHP unit has an electrical output of 220 kW and a thermal output of 270 kW. In continuous operation since 2023, it functions as a dispatchable and plannable baseload energy source and a grid-connected net exporter. Operational flexibility is supported by short-term biogas storage, which allows generation to be adjusted to changing conditions, while black-start and island-mode capabilities enhance system resilience and enable operation during grid outages

Improvement/Innovative feature compared to the previous existing plants: The innovation at Vasen is not new technology but a complete, working system built from proven components. A single on-site resource — manure — now supplies the farm's entire electricity and heat demand and returns organic fertilizer to the land, taking the farm from grid consumer to self-reliant producer. The installation runs fossil-free and retains island-mode capability, and the former manure tank now serves as digestate storage — closing the nutrient loop on site. It demonstrates, on a working farm, that one local resource can carry a farm's full energy needs as an integrated whole.

Performing metrics: The installation's strength lies in system efficiency — a single local resource meets the farm's full energy demand. From manure alone, it produces more than seven times the farm's previous total energy consumption, delivering 220 kW of electricity and 270 kW of heat (a roughly 45:55 electricity-to-heat split), covering the farm's own needs and exporting surplus to the grid. Operation is entirely fossil-free: the CHP gas engine uses spark ignition to ignite the methane, with no fossil fuel needed for ignition or backup.

Integration with already existing plants? The biogas and CHP installation were newly built, but it was integrated with the farm's existing infrastructure rather than replacing it. The consumption units use the farm's existing equipment, now supplied from the new energy source, and the farm's former manure tank was converted into digestate storage. This approach keeps the integration threshold low: the new energy system connects to what the farm already has.

TRL: The core biogas and CHP technology is commercially mature (TRL 8–9). As a single-designed installation, the integrated system is at TRL 6.

ECONOMIC ASPECTS

Investment /financiers: Vasen's installation was financed through farm equity and public support instruments, Klimatklivet (Swedish Environmental Protection Agency).

CAPEX/OPEX: Not disclosed (privately owned pilot).

Initiation and challenges: The project was initiated by the farm itself. The main challenges were practical: dimensioning the plant to the farm's own energy demand and establishing reliable island-mode operation against a dead grid.



Figure 15. Vasen Farm.

ENVIRONMENTAL ASPECTS

The system delivers climate benefits through three main mechanisms. First, capturing methane from manure through anaerobic digestion prevents emissions that would otherwise occur during conventional manure storage. Second, the on-site renewable electricity and heat replace previously purchased grid electricity and external heating, reducing fossil energy use. Third, the digestate returned to farmland substitutes for synthetic mineral fertilizer, whose production is fossil-dependent, reducing the need for newly extracted inputs.

SOCIAL ASPECTS

Job creation: Operation of the energy system is integrated into the farm's existing activities. Indirect employment is created across biomass supply chains, engineering, and agro-services

Local value creation: The installation keeps value within the local agricultural system. Renewable energy is produced and used on site, digestate replaces purchased mineral fertilizer within the farm's own cycle, and by covering its own demand and exporting surplus the farm reduces strain on the local grid.

POLICY ASPECTS

The installation is supported by Swedish policy instruments for farm-based biogas. Investment support was

provided through Klimatklivet (the Swedish climate investment programme), and production is supported by the manure-gas premium (gödselgasstöd), a production incentive for manure-based biogas. These instruments reflect national priorities on renewable energy, methane reduction, and agricultural resilience.

FLEXIBILITY ASPECTS

Feedstock flexibility: The installation runs on a single feedstock (manure) which provides a stable, continuous supply throughout the year.

Network integration: Energy is used primarily within the farm's internal grid for electricity and heat, with surplus electricity exported to the external grid. That means: The system can operate both island-mode and connected to local, regional, and national electricity distribution networks. Heat integration with farm buildings and potential district heat connection is included in system design.

Temporal flexibility: Because biogas can be stored and dispatched on demand, production can be timed to periods when it is most needed — during the farm's own peak use, or when the surrounding grid is under strain.

Storage: The installation includes short-term biogas storage (gas holder, 6–18 hours) and digestate storage with up to eight months' capacity, allowing spreading during the growing season and providing both agronomic and regulatory flexibility.

FUTURE DEVELOPMENT

The installation offers opportunities for further expansion, including the use of additional feedstocks to increase biogas production and the development of new energy and nutrient products. These options are currently being explored as part of the farm’s long-term development strategy. Solar PV and woodchip heating are also under consideration, although no investment decisions or implementation schedules have yet been defined.

CONCLUSIONS/RECOMMENDATIONS

The Robusta Gården concept demonstrates how locally available biomass resources can be integrated into farm-based energy systems that produce renewable electricity, heat, and organic fertilizer. The pilot installation at Vasen Farm shows that a single feedstock stream, manure from the farm's own herd, can support continuous biogas production while supplying the farm with renewable energy and returning nutrients to agricultural land.

A key characteristic of the concept is that system design is based on a site-specific energy resource assessment. This approach allows the technical configuration and scale of each installation to be adapted to locally available biomass resources and energy demand. The modular structure further enables stepwise development and potential expansion over time.

The case study illustrates the value of integrating energy production, nutrient management, and agricultural activities within a single system. In addition to renewable energy generation, the concept contributes to methane emission reduction through anaerobic digestion of manure and reduces the need for mineral fertilizers by using digestate.

The concept has been demonstrated at one operational site and is currently being developed for replication through standardized site assessment methods, financing models, and partnership structures. Given the commercial maturity of the core technologies and the availability of agricultural biomass resources in many regions, the concept has potential applicability in other agricultural contexts where suitable feedstocks, supportive policy frameworks, and local stakeholder engagement are present.

From a broader energy system perspective, the Robusta Gården concept highlights the potential role of decentralized farm-based bioenergy systems in providing dispatchable renewable energy that can complement variable renewable electricity sources while supporting regional bioeconomy and climate objectives.

Case study 4: Optimized combination of heat pump and biomass plant, Silkeborg, Denmark

This case study demonstrates how electrification and sustainable biomass can be combined in a single integrated district heating system. Rather than operating as two independent heat production technologies, the heat pump and biomass plant are thermally integrated so that each improves the performance of the other. The concept illustrates how hybrid district heating systems can increase efficiency, reduce dependence on fossil fuels and improve operational flexibility while maintaining a reliable and inexpensive heat supply.

The project consists of an integrated district heating system combining an electrical heat pump with a biomass plant equipped with a flue gas condenser. The biomass plant raises the heat pump outlet temperature and supplies cooling water to the heat pump evaporator well as condensate for defrosting during cold outdoor temperatures. This hybrid plant uses local biomass and electricity for efficient heat production.

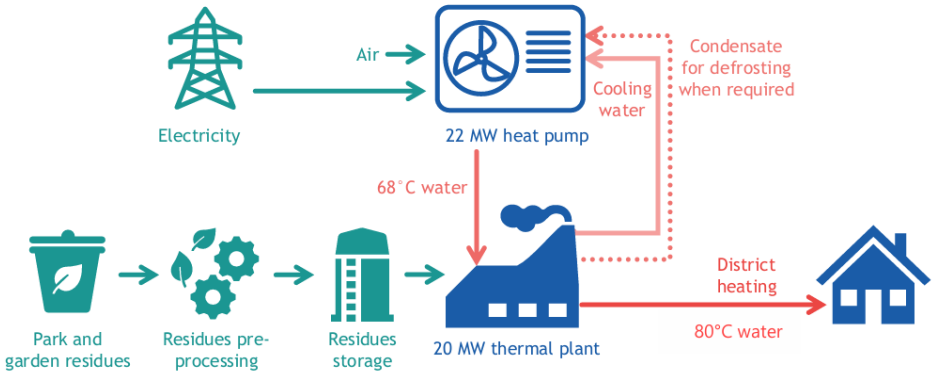


Figure 16. Case study 3: Heat pump and biomass plant hybrid district heating in Silkeborg.

This case illustrates how a combination of technologies can increase overall efficiency. The integration of a biomass plant and electrical heat pump improves the performance of both technologies. Here, the heat pump operates at a high efficiency with a relatively low outlet temperature, and the water temperature is raised to the required district heating temperature by the biomass plant. The biomass plant also provides cooling water to the heat pump and during winter operation, condensate from the thermal plant is used for defrosting the heat pump. This integrated solution results in a highly efficient and resilient system.

ABOUT THE PLANT/SYSTEM

Name of the plant: Silkeborg integrated heat pump and biomass district heating plant.

Type of facility: Hybrid district heating plant.

Owner/operator: Silkeborg Varme A/S (District Heating Utility) part of Silkeborg Forsyning A/S fully owned by Silkeborg Municipality.

Location: Silkeborg, Denmark.

Overview of input and outputs:

- Input: Electricity and biomass from garden and park residues.

- Output: District heating.

Capacity: 22 MW air-to-water heat pump **and** 20 MW biomass plant with flue gas condenser

Main flexibility aspects for this system/process/plant:

- The biomass plant can operate both together with and independently of the heat pump.
- The biomass plant boosts heat pump outlet temperature.
- The biomass plant provides cooling water for the heat pump evaporator.
- The biomass plant provides condensate from the flue gas for defrosting the heat pump during low outdoor temperatures.

History:

- Silkeborg Varme A/S wanted to phase out fossil natural gas for district heating while lowering their CO_2 emission and diversifying their heat supply without relying fully on electricity.
- Upon the 2018 Danish energy agreement that had focus on electrification including electricity-to-district heating, initial experiences with heat pumps showed problems with evaporator icing. In 2019, Dall Energy developed the concept of integrating a heat pump and biomass boiler and applied for a grant from the Danish Energy Technology Development and Demonstration Programme (EUDP) to demonstrate the concept at Halsnæs Supply Company.
- In 2020, EUDP recommended including "heat pump competencies" in the project after which COWI was invited to join as a partner. The resubmitted proposal was granted funding. In 2022, Halsnæs Supply Company decided not to build a new biomass plant and the consortium of Dall Energy and COWI agreed with the EUDP to move the granted project to Silkeborg. In 2024, Dall Energy filed a patent application for the concept. The patent was granted in May 2026.
- The hybrid plant forms part of Silkeborg Varme's wider district heating portfolio, which also includes a 50 MW electric boiler, a large solar thermal plant, thermal storage, and a large natural gas-fired CHP plant along with a very large solar thermal plant (156,000 m2) and other heat production units. Together, these technologies allow the utility to optimise heat production according to heat demand, electricity prices and system conditions while increasing the robustness and flexibility of the overall district heating system.

Investment: Total project budget: Around 44 million € (326 MDKK) The innovative coupling of the technologies was demonstrated in a project with a budget of 2.25 million € (16,81 MDKK) of which 37% was funded by the Danish Energy Technology Development and Demonstration Programme (EUDP)[26].

Suppliers:

- Biomass plant: Dall Energy
- Heat pump: Exodraft
- Advice: COWI

[26] https://eudp.dk/projekter/optimeret-kombination-varmepumpe-biomasse-anlaeg

FEEDSTOCKS

The biomass plant is specifically designed to utilise low-quality biomass like garden and park residues, distinguishing it from conventional wood chips or wood pellets biomass plants.

Garden and park residues are collected by municipalities and handled centrally. Whereas it was previously composted, increased focus on GHG emissions has turned the development towards utilisation for energy purposes. When collected, garden and park waste contains a large share of ash and moisture, and the composition varies over the year. An example is illustrated in Figure 2.

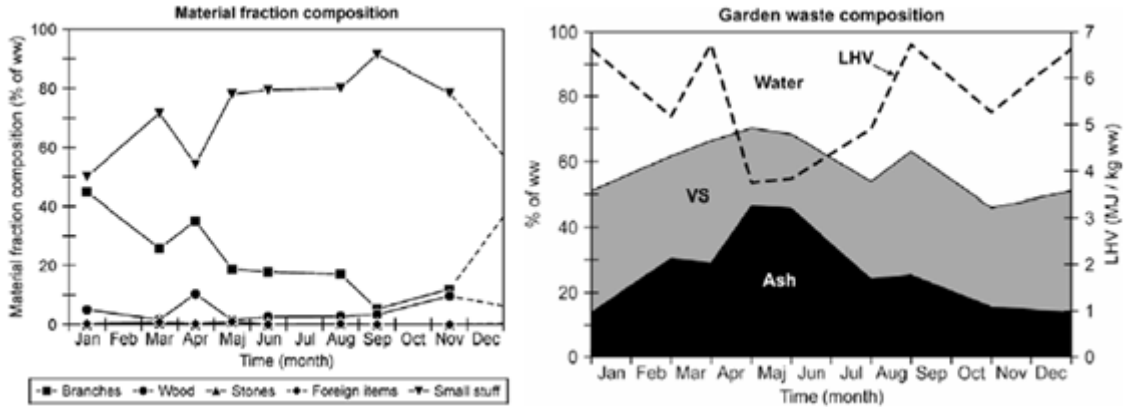


Figure 17. Example of annual variation of collected garden and park waste. The figure to the left shows the annually collected fractions while the figure to the right shows the seasonal variation in moisture content, combustible fraction (VS), "ash content" (left y-axis), and lower heating value (LHV – right y-axis) Data from Aarhus 2003-2007[27].

To be used for energy purposes, garden and park residues needs pre-treatment. The level required depends on the boiler type to utilise the resulting product and generally implies processes like washing, storage, drying, crushing, and sorting before combustion. During this process, stones, soil, plastic waste and metals are removed, and fine fractions unsuitable for combustion are separated and directed to composting, while the remaining coarse woody fraction is used as fuel.

The pre-treatment improves fuel quality, storing ability, and handling. The local annual availability of park and garden residues within the municipality is approximately 3,000 tonnes. This corresponds to 8-10% of the plant's annual demand and the remainder is sourced from other Danish municipalities.

During the first year of operation, Silkeborg Varme experienced significant variations in the structure and homogeneity of the 30,000 tonnes of garden and park residues totally sourced from recycling centres across most of Jutland and on Funen in Denmark. The content of fines led to challenges ensuring uniform fuel feeding into the furnace. Subsequently the two automated fuel cranes in the fuel silo have continuously been mixing the residues to ensure thorough blended before delivery into the feed hopper. The high content of fines also challenged the ash discharge system that was subsequently modified[28]

In case garden and park residues will not be sufficient to supply the plant, the plan is to use Danish wood chips

[27] https://www2.mst.dk/Udgiv/publikationer/2019/06/978-87-7038-084-3.pdf

[28] https://pro.ing.dk/gridtech/artikel/koeler-roeggas-med-varmepumpens-kulde-silkeborg-henter-ekstra-megawatt-ud-af-vaadt-haveaffald

sourced from forest operations or wood processing industries as backup fuel. Potential future feedstocks further include residues from the food and feed industries such as nutshells to supplement the garden and park biomass.

The electricity input for the heat pump is from the Danish grid. Electricity produced in Denmark is ~95% based on renewables and this is expected to increase over time.



Figure 18. The crane system is used actively to mix various fuel deliveries into a more uniform fuel quality in the fuel storage. (Photos: Arkikon and Morten Tony Hansen)

PRODUCTS

The hybrid plant produces hot water for the local district heating network which, along with other production units, provides heating for around 55,000 consumers. The hybrid concept was developed to support Silkeborg Varme's transition away from natural gas by providing a cost-effective, robust and low-carbon district heating solution. Using locally sourced biomass helps stabilize heat prices by reducing dependence on fossil fuels and volatile electricity markets. The project is intended as a demonstration for wider deployment. It is a relevant case for other cities with similar ambitions to defossielise district heating while maintaining reliable heat supply.

TECHNICAL DATA

The hybrid plant includes a 22 MW air-to-water heat pump provided from Exodraft Energy and a 20 MW biomass plant with a flue gas condenser from Dall Energy. This is supported by an integrated heat pump-biomass control strategy. The system integration enables the biomass plant to enhance heat pump performance while allowing both technologies to be optimized with the existing district heating infrastructure.

The 20 MW biomass boiler plant uses a patented staged combustion technology which enables combustion of garden and park waste that can be troublesome in more traditional biomass boilers due to the varying size distribution, moisture content and high ash content. The fuel is fed into a bed where it is gasified. When the gases flow through the unburned fuel layer, a natural filtering effect occurs as particles and fly ash are trapped by the fuel instead of being carried away into the combustion and flue gas ducts.

Table 8. Summary of technical data of the hybrid plant.

Indicator	Value
Heat pump capacity	22 MW
Biomass plant	20 MW
Operating mode	Parallel operation with independent operation of the plants possible
Increase in COP	~10%
Increase in heat production	~10%
Heat pump outlet temperature	68°C
Final DH temperature	≈78–83°C



Figure 19. The Dall Energy furnace and boiler system enables staged combustion of pre-treated garden and park residues. (Photos: Morten Tony Hansen)

As the conversion temperature is kept rather low, the system does not need neither particle separation nor injection of agents to reduce NOx emissions. The fuel layer itself captures the ash at the bottom. When the gases reach the top of the furnace, secondary and tertiary air is added, whereby the gas is burned out completely

at high temperature. The hot flue gas is led through a quench that lowers the temperature and removes the remaining particles. After the quench, the flue gas is led into a two-story scrubber filled with specially manufactured glass elements. Using the cold-water circuit from the heat pump, the flue gas in the scrubber is cooled and the water vapours condense completely while releasing the vaporisation heat into the district heating water.

A high moisture content in the fuel is positive and preferably up to 60 percent to keep the yield in the scrubber high. When the flue gas leaves the chimney, it has cooled down to approximately 30 degrees, which provides for an overall efficiency of the system of over 100 percent calculated on basis of the lower heating value of the fuel.

Heat is thus generated through the combined operation of the heat pump and biomass plant. The heat pump is designed to produce water at approximately 68°C, where it operates with a relatively high coefficient of performance (COP). The biomass plant raises the water temperature the remaining 10-15°C (to the required level) before the water enters the district heating network. By sharing the temperature lift between the two technologies, the heat pump can continue operating under more favorable conditions, reducing electricity consumption while maintaining a high COP. The plants can also be operated flexibly, and the biomass plant can be downregulated to 10% of load with rapid ramp rates[29]. The technical data is summarized in *Table 8*.

The flue gas condenser in the Silkeborg hybrid system performs multiple functions. In addition to recovering heat from the flue gases and increasing overall boiler efficiency, it is thermally integrated with the air-to-water heat pump. The condenser provides cooling water to the evaporator to support heat pump operation. During cold outdoor conditions, ice can accumulate on the evaporator of an air-to-water heat pump. This reduces heat transfer efficiency and requires periodic defrosting cycles that temporarily interrupt heat production and consume additional energy. In the Silkeborg hybrid plant, warm condensate from the biomass plant is used to assist the defrosting process. This reduces the energy needed for defrosting, allowing the heat pump to operate more efficiently and increasing its overall COP during winter operation.

The novelty of this hybrid plant lies in the system integration for temperature boosting, providing cooling water from the biomass plant to the heat pump and using condensate from the flue gas condenser for defrosting the heat pump. This allows both technologies to operate more efficiently than they would as stand-alone systems and is one of the distinguishing features of the Silkeborg hybrid plant. The cold water generated by the heat pump is furthermore used to increase the efficiency of the large solar thermal collectors.

The hybrid plant is integrated into Silkeborg Varme's wider district heating system, which also includes a 50 MW and a 30 MW electric boiler, thermal storage, and a large natural gas-fired CHP plant (100 MWe) along with a very large solar thermal plant that with 156,000 m2 collectors is likely the World's largest, and other heat production units. Rather than operating as a stand-alone facility, the hybrid plant complements the existing production portfolio, enabling heat production to be optimised across the entire district heating system according to heat demand, electricity prices and operational conditions. This integrated approach increases supply security while providing greater operational flexibility than any single production technology alone.

[29] https://dallenergy.com/en/projects/20-mw-silkeborg-dk/



Figure 20. Three industrial heat pump compressors are supplied through the existing 10 kV transformer. (Photos: Morten Tony Hansen and Arkikon)

Power supply for the heat pump is different from other plants since Silkeborg Varme has been connecting the plant through the existing high-voltage transformer at the gas-fired plant reducing the capex significantly. The heat pump plant is supplied by 10 kV which required using large industrial grade compressors (in this case from GEA) instead of the more normal small modular 400V types. The system thus fits into the existing organisational experience with the high-voltage market where Silkeborg Varme has for long been active. The plant is therefore connected to the TSO's (Energinet) balancing markets for mFRR (manual frequency restoration reserve) and MLT (Manual Regulation Power) respectively[30].

ECONOMIC ASPECTS

The total investment budget for the two large units in the hybrid plant was DKK 326 million (approx. € 44 million)[31] .A demonstration project has developed the technology integration part. The budget was 2.25 million € (16,81 MDKK)[32]. This was covered by the project partners; Silkeborg Varme A/S, Dall Energy, and COWI as well as by support from the Danish Energy Technology Development and Demonstration Programme (EUDP). The EUDP funds covered 37% of the project budget. The project was initiated by Dall Energy, with their ambition to demonstrate an integrated biomass and heat pump concept that had already received EUDP support for another location. Silkeborg Varme later became the demonstration partner as this was a good fit with their plans to expand renewable district heating while reducing dependence on natural gas and diversifying supply.

The implementation required close collaboration between Silkeborg Varme, Dall Energy, suppliers, and Silkeborg Municipality. The municipality approved the district heating project proposal in October 2021, and an environmental assessment was completed before construction of the heat pump plant. The project also involved an EU procurement procedure for the heat pump. Before the investment decision, different technology combinations and operational scenarios were evaluated through detailed techno-economic modelling. This helped identify a solution that balanced energy efficiency, operational costs and future flexibility while providing confidence for both the utility and its board.

Although detailed operating costs are commercially confidential, the integrated concept reduces operating costs by increasing the heat pump COP, reducing electricity consumption and allowing operation to respond to electricity market prices.

[30] https://pro.ing.dk/gridtech/artikel/traekker-stroemmen-baglaens-gennem-transformeren-silkeborg-forsyning-genbruger-hoejspaending-til-22
[31] https://via.ritzau.dk/pressemeddelelse/13670622/klimavenlig-fjernvarme-i-silkeborg-er-kommet-et-stort-skridt-naermere?publisherId=13560203
[32] https://eudp.dk/projekter/optimeret-kombination-varmepumpe-biomasse-anlaeg

In the larger picture the hybrid plant contributes significantly to maintain a stable heating price that is much less prone to volatile fossil fuel prices. The flexible nature of the hybrid plant plays a crucial role in this development. The control system calculates the marginal production price for each individual unit on a daily basis:

- At low or negative electricity prices, the 22 MW heat pump and the 80 MW electric boilers will run at full load
- At high electricity prices, the electric units are limited, and the biomass plant takes over as base load together with the heat storages
- During electricity price peaks, the plant can turn down its own electricity consumption and instead run operate the two existing gas turbines at the CHP plant to deliver 100 MW of power directly to the electricity grid within a few minutes[33]

ENVIRONMENTAL ASPECTS

The primary environmental objective of the project is to support the transition away from fossil natural gas by integrating renewable electricity and sustainable local biomass for district heating production. The biomass plant is designed to utilise locally sourced garden and park biomass, including residual biomass from landscape maintenance, infrastructure development and municipal green waste. The use of these resources contributes to replacing fossil fuels while making use of local biomass. The integrated concept supports Silkeborg Varme's ambition to deliver climate-neutral district heating in a cost-effective and robust manner. By reducing both electricity consumption and biomass demand for each unit of delivered heat, the integrated concept also improves overall resource efficiency.

The investment in the new plant is a part of a large development plan that since 2014 has enabled Silkeborg Varme to reduce the total CO_2 emission by 66%. The climate footprint for Silkeborg Varme has been reduced by 25% since the hybrid plant started its operation in 2025[34]. This will be reduced further when hybrid plant will be in operation for the entire heating season, expected in 2027. Additionally, the continued transition away from use of fossil fuels in the Danish electricity and gas systems will further reduce the climate impact from Silkeborg district heating.

SOCIAL ASPECTS

The project demonstrates how collaboration between a district heating utility, technology providers, engineering consultants and public funding programmes can accelerate the deployment of innovative district heating solutions. Throughout the implementation phase, Silkeborg Forsyning worked closely with Silkeborg Municipality, technology suppliers, and engineering partners. The project milestone marked by the topping-out ceremony brought together project partners, municipal representatives and employees, reflecting strong local support for the transition towards climate-friendly district heating. The hybrid plant will contribute to supplying approximately 55,000 district heating consumers with a more sustainable heat supply.

POLICY ASPECTS

The hybrid project aligns with the objectives of the Danish Climate Act by supporting the transition towards a 70% reduction in greenhouse gas emissions by 2030 and climate neutrality by 2050 through increased electrification and more efficient use of renewable biomass resources. Locally, the hybrid plant forms part of

[33] https://pro.ing.dk/gridtech/artikel/fra-naturgas-klemme-til-strategisk-schweizerkniv-saadan-sikrer-silkeborg-sig-mod-prischok-og
[34] https://pro.ing.dk/gridtech/artikel/fra-naturgas-klemme-til-strategisk-schweizerkniv-saadan-sikrer-silkeborg-sig-mod-prischok-og

Silkeborg Varme's strategy to phase out fossil natural gas and develop a more climate-friendly district heating system. The project demonstrates how public funding, municipal planning, and utility investment can be combined to accelerate the deployment of integrated renewable heating technologies.

The hybrid plant forms part of a phased long-term investment strategy developed by Silkeborg Forsyning to achieve CO_2-neutral district heating. The first implementation phase combines the biomass plant, the large air-to-water heat pump with an electric boiler, illustrating how strategic planning and public investment can support the gradual decarbonisation of district heating systems.

FLEXIBILITY ASPECTS

The hybrid concept combines electricity and biomass input for heat production to provide greater operational flexibility than either technology could achieve alone. For fuel input the biomass plant is designed to utilise locally sourced biomass, and they also have a strategy to supplement with Danish wood chips if enough garden and park biomass are not available. The project also includes the future possibility of using additional residual biomass streams, such as by-products from the food and feed industries. This flexible fuel strategy reduces dependence on a single biomass source.

The project demonstrates system integration between an electrical air-to-water heat pump and a biomass plant within the district heating network. The hybrid plant reduces dependence on a single energy carrier by combining electricity and biomass, improving supply robustness under varying electricity market conditions.

The hybrid concept provides value at both ends of the electricity price spectrum. During periods of low or negative electricity prices, the heat pump can maximize electricity-based heat production. During periods of high electricity prices, the biomass plant can supply heat while reducing electricity consumption and limiting operating costs.

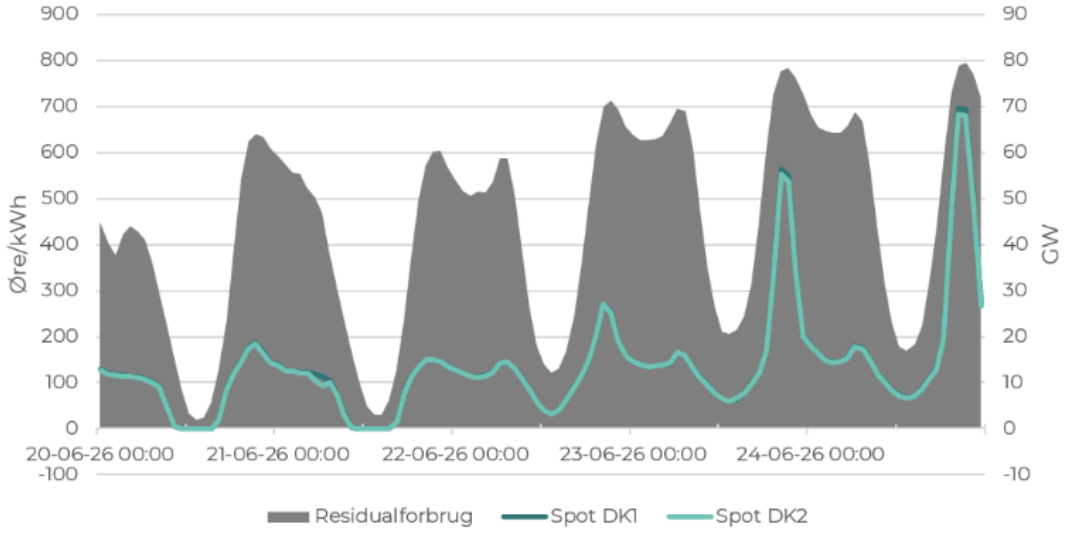


Figure 21. Relationship between residual electricity demand and spot electricity prices in Northern Europe over a representative five-day period. Lower residual demand, driven by high wind and solar generation, is generally associated with lower electricity prices, whereas higher residual demand results in increased electricity prices. The figure illustrates the value of flexible hybrid heat production systems[35].

[35] Green Power Denmark, "Hitzeflaute, snorkelpriser og hellbrise: Sommeren har mange sjove energiord", 1 July 2026. Link here.

The value of this operational flexibility is expected to increase as electricity systems become more dominated by variable renewable generation. *Figure 21* illustrates the relationship between residual electricity demand (electricity demand minus wind and solar generation) in Northern Europe and spot electricity prices in Denmark. Periods of low residual demand generally coincide with lower electricity prices, whereas high residual demand is associated with price spikes. In the Silkeborg hybrid system, heat production can therefore be shifted between the heat pump and the biomass plant depending on electricity market conditions. During periods of high electricity prices, the biomass plant enables district heating production to be maintained while reducing electricity consumption from the heat pump. Conversely, when electricity prices are low, the heat pump can operate at high efficiency while the biomass plant provides temperature boosting and operational support. The two technologies are thermally integrated to increase the efficiency of both technologies compared with stand-alone operation. On a seasonal scale, integration is particularly beneficial during winter, when air-source heat pumps typically experience reduced performance. By allowing the heat pump to operate at a maximum outlet temperature of approximately 68°C while the biomass plant provides the final temperature lift, the system maintains a high coefficient of performance (COP). In addition, the use of warm condensate from the biomass plant for heat pump defrosting further improves winter performance by reducing the energy required for defrost cycles.

The integrated system allows for operations to be optimized on an hourly basis according to electricity prices, fuel costs, weather conditions and district heating demand. Together with thermal storage, this allows the heat pump to operate during periods with favorable electricity prices and low electricity-related emissions while biomass provides temperature boosting and operational security.

Both units can be operated individually should this be the favourable option in the electricity grid. The new system contributes to the ability for the total assembly of generation technologies to maintain a stable heating price in Silkeborg and keep it less prone to volatile market prices for fossil fuel and electricity. By keeping track of the electricity market and the marginal production price for each individual unit in Silkeborg, the dispatch is determined:

- At low or negative electricity prices, the 22 MW heat pump and the 80 MW electric boilers will run at full load
- At high electricity prices, the electric units are limited, and the biomass plant takes over as base load together with the heat storages
- During electricity price peaks, the plant can turn down its own electricity consumption and instead run operate the two existing gas turbines at the CHP plant to deliver 100 MW of power directly to the electricity grin within a few minutes.

FUTURE DEVELOPMENT

The Silkeborg hybrid project serves as a demonstration of how biomass and heat pump technologies can be integrated to improve the efficiency, flexibility and robustness of district heating systems. For Silkeborg Varme, the hybrid plant represents an important milestone in the transition away from natural gas towards a fossil-free district heating system. As the district heating network continues to develop, the utility expects to further strengthen system integration through additional renewable heat sources, thermal storage and sector coupling opportunities. The utility expects to install additional 20 MW of capacity but has not yet decided on the technology. Geothermal energy is being discussed.[36]

The project also demonstrates an integrated concept that technology providers such as Dall Energy intend to replicate in other Danish and European district heating systems.

[36] https://danskfjernvarme.dk/aktuelt/nyheder/2026/goddag-til-fossilfri-diversitet-i-silkeborg

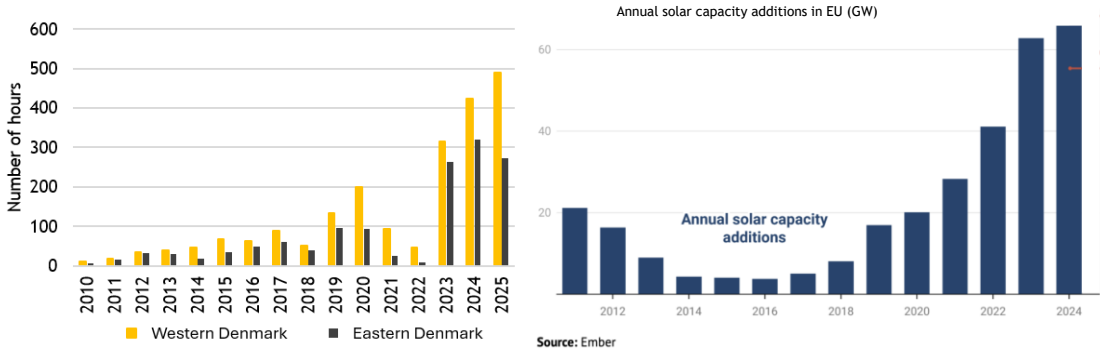


Figure 22. Development in the annual number of hours with negative electricity prices in Western and Eastern Denmark (left) and annual solar PV capacity additions in the European Union (right). The increasing deployment of variable renewable electricity generation is contributing to greater electricity price variability, highlighting the growing value of flexible energy systems that can adapt their operation to changing market conditions [37].

The increasing penetration of wind and solar power is expected to result in greater volatility in electricity prices, including both more frequent periods of very low or negative prices and more periods with high prices. Figure 22 illustrates the rapid increase in the number of hours with negative electricity prices in Denmark together with the continued growth of solar photovoltaic deployment across Europe. As electricity market variability increases, hybrid systems such as the Silkeborg concept become increasingly valuable because they can adapt heat production to changing market conditions while maintaining reliable district heating supply.

CONCLUSIONS/RECOMMENDATIONS

Within the transition away from fossil fuels, the hybrid biomass-heat pump concept demonstrates how locally available biomass residues can complement electrification by improving heat pump performance, reducing both electricity and biomass consumption.

Although developed for Silkeborg's district heating network, the concept has broader applicability. The project partners highlight that many Danish and European cities share similar ambitions to de-fossilize district heating while maintaining reliable and cost-effective heat supply. By combining electrification with locally available biomass residues, the concept offers a pathway to reduce dependence on fossil fuels while avoiding complete reliance on electricity alone.

The Silkeborg hybrid plant demonstrates that biomass can complement large-scale heat pumps rather than compete with them. Here biomass is used where it provides the greatest value by raising supply temperatures, supporting heat pump performance and ensuring reliable operation during periods when electricity-based heating is less favorable. The result is a diversified and flexible district heating system rather than reliance on a single technology.

The hybrid plant uses regionally available biomass resources and commercially available heat pump technology. This approach could be adapted to other district heating systems where suitable biomass resources and heat demand exist. Here, the specific system design, available biomass resources, and local heat demand should be considered when transferring the concept to other locations.

[37] Sources: Energi Data Service (processed by Ea Energy Analyses) and Ember.



Figure 23. The new hybrid plant is a part of large system with many generation technologies. With the new plant in the foreground, the existing natural gas fired CHP plant and large heart storages can be seen in the background. (Photo: Arkikon)

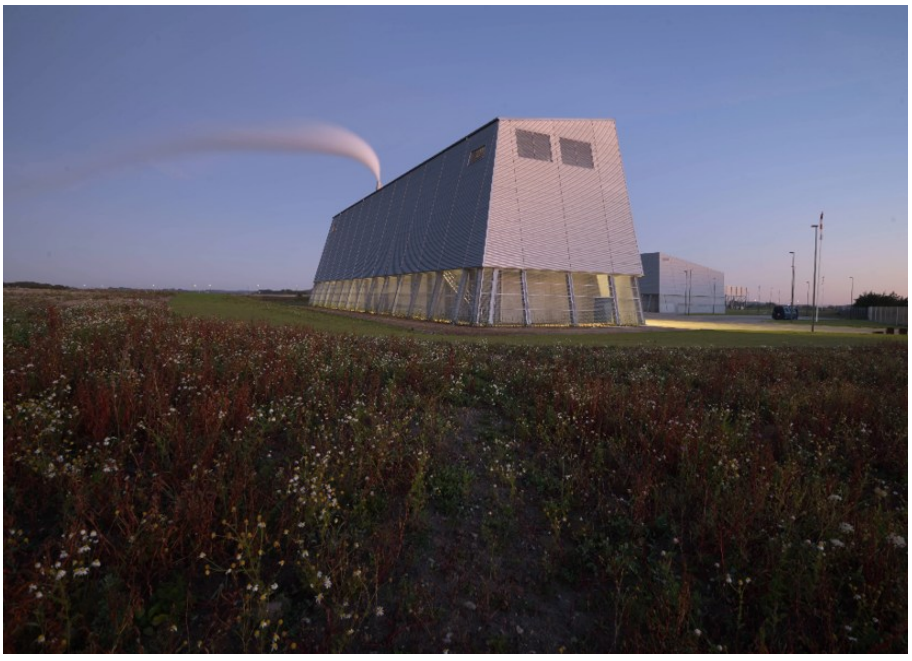


Figure 24. Silkeborg hybrid district heating plant. (Photo: Arkikon)

Flexibility Potential

HIGHLIGHTS AND BENEFITS ACROSS THE FOUR CASES

This chapter systematically evaluates the results of the four case studies. The analysis is guided by three research questions to show how flexibility is implemented in the respective projects and what specific advantages result from it. A brief overview of future improvements and further developments is provided at the end.

Similarities within the four cases

Despite the different technological configurations of the project ranging from agricultural use (Dairy, Pig, and Vasen Farm) to hybrid technical symbiosis (Silkeborg), significant similarities in flexibility can be identified:

Hybrid Resource Strategy: Almost all projects use a combination of biomass and renewable energies (especially photovoltaics). This combination is essential to cover both daily fluctuations as well as seasonal requirements and nighttime peak loads.

Operating Mode and Maturity: Three investigated systems (farms) are in operational mode (TRL 9), with a focus on decentralized structures that combine generation, storage, and consumption within limited boundaries. This reduces dependence on external factors and increases local security of supply.

Multimodal Energy Provision: There is a commonality in the flexibility of outputs; three out of four systems are designed to provide both electrical energy and thermal energy (heat). Heat is provided by all projects investigated for their own use or to supply a district heating network.

Economic and Ecological Coherence: In all cases, the use of flexibility leads to a simultaneous reduction in CO2 emissions and a reduction in operating costs.

Contributions and benefits from the flexibility

The way the projects use flexibility varies depending on the technical focus and objectives:

Resources and Products: While all projects provide heat, two of the systems use flexibility to produce fertilizers as a local resource. In the Vasen Farm, storing digestate for up to eight months allows for the application of nutrients at the right time during the growing season.

Technical Synergies and Flexibility: There are differences in the system portfolios. The agricultural operations (Dairy, Vasen & Pig Farm) use flexibility primarily for temporal and material optimization.

Pig breeding Farm Storage: By using a buffer tank, heat production is decoupled from current demand, enabling flexibility ranging from hours to days.

Vasen Farm Nutrient Management: The ability to store digestate for up to eight months allows the farms to precisely align nutrient release with the agricultural growing season.

In the industrial model (Silkeborg), technical symbiosis is the main focus. The system uses the biomass plant not only for energy generation but also to support the heat pump: the biomass provides cooling water for the evaporator, and the condensate from the flue gas is used for defrosting the heat pump at low ambient temperatures. This represents a highly optimized technical flexibility that increases the efficiency of the overall system.

Table 9. Overview of details of flexibility aspects in all four case studies.

Case study no. and name	Renewable resource	Feedstock	Market/Pilot/TLR	Energy outputs and inputs	Social relevant services	Local grid, markets, intern. trade, community cooperation	Products	Non energy products	Temporal flexibility	Others- start up time, storage, environmental aspects
Case 1- Dairy Farm - with Biogas CHP and PV, District Rostock, Germany	PV	Cow manure (slurry & solid, year-round) + Crop residues (silage, straw: seasonal)	TLR 9, in work.	Input: solar irradiation (PV) and biogas. Output: Electricity for the farm and to sell; heat and hot water (pipes) for the farm	Supports local employment and retains economic value within the community by keeping operation, maintenance, and servicing activities on-site, reducing financial outflows to external suppliers.	Surplus electricity from both CHP and PV to be exported to the public grid.	Electricity, Heat	Organic fertilizer	Seasonal adaptation (PV and feedstock), Winter efficiency (year-round cow manure), Grid integration and market flexibility enabled by the farm's bi-directional metering and EEG feed-in arrangement, which allows surplus electricity from both CHP and PV to be exported to the public grid.	Manure as continuous year substrate that moderates the seasonal variability. PV covers daytime demand peaks while biogas CHP fills supply gaps during night-time hours and overcast conditions.

Case study no. and name	Renewable resource	Feedstock	Market/Pilot/TLR	Energy outputs and inputs	Social relevant services	Local grid, markets, intern. trade, community cooperation	Products	Non energy products	Temporal flexibility	Others- start up time, storage, environmental aspects
Case 2- Pig breeding Farm with Wood Chip Heating and PV, Panzow, Germany	PV	Wood chips (local, storable)	TLR 9, in work.	Inputs: wood chips (biomass boiler feedstock), solar irradiation (PV). Outputs: heat for pigsties, residential buildings and warehouse; electricity for exhaust ventilation, lighting, and water pumps.	Local biomass procurement supports the regional wood supply chain and contributes to the circular economy.	Surplus electricity from both CHP and PV to be exported to the public grid. Sourcing wood chips locally supports forest management activities, which in turn benefits regional employment and helps keep carbon locked in the landscape.	Heat, Electricity	x	The hot-water buffer tank decouples heat production from instantaneous demand (temporal flexibility over hours to days), Seasonal adaptation (PV>high summer), Winter efficiency (storable wood chips)	Replacing natural gas with wood chip biomass has an economic benefit, also avoids direct combustion emissions and the indirect carbon footprint typically associated with fossil fuel extraction, refining, and large-scale infrastructure distribution. The farm also eliminates the risk of methane leaking during gas extraction and distribution. Future battery storage and smart load management upgrades would further increase self-consumption of solar electricity and reduce peak demand charges.

Case study no. and name	Renewable resource	Feedstock	Market/Pilot/TLR	Energy outputs and inputs	Social relevant services	Local grid, markets, intern. trade, community cooperation	Products	Non energy products	Temporal flexibility	Others- start up time, storage, environmental aspects
Case 3- Robusta Gården Concept – Decentralized Farm-Based Bioenergy Systems. Pilot: Vasen Farm, Sweden	x	Cow manure (year-round)	The core biogas and CHP technology is TRL 8–9, the integrated system is at TRL 6. In work.	Input: Biogas from manure. Output: Electricity and heat	System creates local resources in fertilizer production, as well as indirect employment in biomass supply chains, engineering, and agro-services. Today the farm produces more than seven times its previous energy consumption >Supply security, Environmental friendliness	Surplus electricity from CHP to be exported to the public grid	Heat, Electricity	Organic fertilizer	In the short term, biogas storage lets the CHP unit adjust its output (6-18 hours) to match the farm's demand, providing plannable, dispatchable energy.	Capturing methane from manure through anaerobic digestion prevents emissions that would otherwise occur during conventional manure storage. On-site renewable electricity and heat replace previously purchased grid electricity and external heating, reducing fossil energy use. Over the longer term, digestate storage of up to eight months allows nutrients to be applied at the right point in the growing season. Furthermore, the application of digestate serves as a substitute for fossil-based fertilizers.

Case study no. and name	Renewable resource	Feedstock	Market/Pilot/TLR	Energy outputs and inputs	Social relevant services	Local grid, markets, intern. trade, community cooperation	Products	Non energy products	Temporal flexibility	Others- start up time, storage, environmental aspects
Case 4- Optimized combination of heat pump and biomass plant, Silkeborg, Denmark	Heat pump	Low-quality biomass: garden and park residues; Danish wood chips as backup	TLR X???, in work	Input: Electricity for heat pump from grid (95% renewable based) and biomass from garden and park residues. Output: hot water for district heating	Generation of hot water that contributes to providing heating for around 55,000 consumers> Supply security, Environmental friendliness	Locally sourced biomass helps stabilize heat prices by reducing dependence on fossil fuels and volatile electricity markets. Hybrid plant enabling heat production to be optimized across the entire district heating system according to heat demand, electricity prices and operational conditions.	Heat, Cooling water	Biomass plant provides cooling water for the heat pump evaporator and condensate from the flue gas for defrosting the heat pump during low outdoor temperatures.	Hourly optimization, Seasonal adaptation, Winter efficiency	Storage integration; De-fossilization of district heating; Biomass plant can operate both together with and independently of the heat pump. By sharing the temperature lift between the two technologies, the heat pump can reduce electricity consumption while maintaining a high COP.

Highlights

The analysis of the case studies provides key insights that can be considered "highlights" for the implementation of decentralized flexibility systems:

Technological Maturity and Combination with Renewables: Flexibility arises through the intelligent connection of systems. The combination of PV with biomass and the coupling of heat pumps with biomass plants show that flexibility can be significantly increased through technical symbiosis. In the case of the Dairy farm, the technologies involved (biogas CHP, biomass boiler, crystalline silicon PV) are at TRL 9, and the supporting policy instruments (EEG, KfW, BMWK) are established and accessible. The main barrier is not technical or regulatory in nature, but the initial capital costs. These could be supported through subsidies.

Decentralized Resilience: The projects demonstrate that decentralized systems can build high resilience to volatile market prices and grid fluctuations through the integration of storage and hybrid generation types, without jeopardizing local security of supply.

Social and Regional Integration as well as Economic Value Creation: The flexibility of the projects enables the creation of social value beyond pure energy generation. Local employment is supported, keeping economic value through operation, maintenance, and service on-site, thereby reducing financial outflows to external suppliers. Furthermore, it includes the strengthening of regional supply chains (e.g., local forest management) and the provision of valuable resources such as fertilizer. It thus also makes a direct contribution to local agriculture and general security of supply.

Ecological Benefit: All systems reduce CO_2 emissions. Additionally, the local procurement of wood chips supports regional forestry, which helps to sequester carbon in the landscape.

Future Developments

Several of the case studies have opportunities to further enhance flexibility and system integration. At the Pig breeding farm, additional photovoltaic (PV) capacity, battery storage, and smart load management of equipment such as ventilation systems and pumps could increase energy self-sufficiency and reduce exposure to electricity price volatility.

At the Dairy farm, future participation in peer-to-peer (P2P) energy trading schemes could create new opportunities to monetize surplus electricity and strengthen integration with the local energy community.

The Silkeborg biomass plant could further expand its operational flexibility through the use of additional residues from the food and feed industry, such as nutshells, broadening the range of available feedstocks.

Similarly, the Vasen Farm system has been designed with future expansion in mind. Potential developments include the incorporation of additional feedstocks to increase biogas production and the development of new energy- and nutrient-based products. The farm is also evaluating the integration of solar PV and woodchip heating, although no investment decisions or implementation timelines have yet been established.

Conclusions & final recommendations

The three farms in this report started with the same problem: dependence on energy sources they could not control and arrived at different solutions using the same underlying logic. Dairy Farm turned its manure and crop residues into a continuous energy supply. Pig breeding farm replaced a gas bill with wood chips pile. Vasen uses cow manure into a continues input for energy generation. Neither farm required experimental technology, exceptional policy support, or unusual financial resources. All three are working.

What the cases demonstrate collectively is that decentralized energy in agriculture is not a niche or a pilot. It is a commercially mature, operationally proven pathway for farms to reduce costs, cut emissions, and insulate themselves from the price shocks that have destabilized European agriculture twice in the past decade. The

technologies involved: biogas CHP, biomass boilers, crystalline silicon PV are all at TRL 9. The policy instruments that support them are established and accessible. The main barrier is not technical or regulatory. It is the upfront capital cost, and that is a solvable problem.

These recommendations follow from the evidence in this report:

- **Prioritize farm-scale energy system design over single-technology deployment.** The presented examples illustrate how a modular, site-specific system can exploit existing biomass and energy potentials. By combining multiple sources, the necessary flexibility is created; a modular construction enables stepwise expansions—e.g., the integration of additional raw materials or new energy and nutrient products. Another important issue concerns efficiency. When biogas plants lack heat-utilization mechanisms, their efficiencies drop compared to plants equipped with thermal recovery systems. A PV array without a dispatchable backup is vulnerable to the gaps it cannot fill. Policy instruments and agricultural advisory services should encourage integrated system design, matching technologies to the farm's specific demand profile, feedstock availability, and grid connection, rather than incentivizing individual components in isolation.
- **Address the battery storage gap.** REopt simulations identified battery storage as the highest-impact near-term upgrade at D**airy and Pig breeding** farm. This is a finding that generalizes: across Germany's agricultural biogas and biomass heating sector, electrical storage is the missing layer that would allow farms to increase solar self-consumption, reduce grid imports, and begin participating in local energy markets. Current investment support instruments do not yet adequately incentivize farm-scale battery storage in combination with existing renewable systems. Closing this gap would unlock flexibility that is already latent in thousands of installed systems.
- **Create conditions for farm-scale P2P energy trading. All presented** farms currently feed their surplus electricity into the grid (in Germany under fixed EEG tariff schemes). The DENA 2030 analysis shows that local P2P trading could reduce electricity costs by up to 20% for participating consumers and deepen the integration of distributed renewable generation into regional energy markets[38]. Dairy Farm, with its continuous CHP surplus, and Pig breeding farm, with its summer PV surplus, are natural candidates for this transition. Technology exists. The economic case exists. What is needed is the regulatory framework to make it possible.

Similarly, Silkeborg Varme - in the long-standing transition away from fossil fuels with climate consequences as well as fluctuating market prices - encountered that electrifying the full heat generation portfolio would not release the heat generation from very volatile prices. The hybrid solution does that. It paves the way for stable heat prices that is key to a successful district heating company with happy customers. Additionally, the biomass plant and the heat pump operate as an integrated system, with each technology supporting the other to maximize efficiency and resilience. The biomass plant also provides cooling water to the heat pump and during winter operation, condensate from the thermal plant is used for defrosting the heat pump.

[38] German Energy Agency - DENA. (2023). Das dezentralisierte Energiesystem im Jahr 2030: Ein systemischer Bottom-up-Ansatz zur Marktintegration dezentraler Verbrauchs- und Erzeugungseinheiten [The decentralised energy system in 2030: A systemic bottom-up approach to the market integration of decentralised consumption and generation units]. Link.


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Technology Collaboration Programme