RES4LIVE

ENERGY SMART LIVESTOCK FARMING
TOWARDS ZERO FOSSIL FUEL CONSUMPTION

Inventory of RES4LIVE best practices

Deliverable 6.5

WP6. Clustering through stakeholders engagement

Project title

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ABBREVIATIONS

BP	:	Biogas Plant
BHE	:	Borehole Heat Exchanger
BioCNG	:	Biogas-Based Compressed Natural Gas
BTES	:	Borehole Thermal Energy Storage
CNG	:	Compressed Natural Gas
CO_2	:	Carbon Dioxide
DC	:	Direct Current
HP	:	Heat Pump
HVAC	:	Heating, Ventilation, and Air Conditioning
LED	:	Light-Emitting Diodes
NH_3	:	Ammonia
PV	:	Photovoltaic
PVT	:	Photovoltaic-Thermal (collectors)
RES	:	Renewable Energy Source(s)
SWOT	:	Strengths, Weaknesses, Opportunities, Threats
WP	:	Work Package

PARTNERS SHORT NAMES

AUA - AGRICULTURAL UNIVERSITY OF ATHENS

UNIBO – UNIVERSITY OF BOLOGNA

ATB - LEIBNIZ INSTITUTE FOR AGRICULTURAL ENGINEERING AND BIOECONOMY

EV ILVO - RESEARCH INSTITUTE FOR AGRICULTURE, FISHERIES AND FOOD

UGENT - GHENT UNIVERSITY

CERTH - CENTRE FOR RESEARCH AND TECHNOLOGY-HELLAS

AU - AARHUS UNIVERSITY

LVAT - LEHR- UND VERSUCHSANSTALT FÜR TIERZUCHT UND TIERHALTUNG GROß KREUTZ E.V.

PSYCTOTHERM - G. LIGEROS & SIA OE

PLEGMA LABS- PLEGMA LABS TECHNOLOGIKES LYSEIS ANONYMOS ETAIRIA

CRMT SAS - CENTRE DE RECHERCHES EN MACHINES THERMIQUES

TERRA - TERRA ENERGY

MG SUSTAINABLE - MG SUSTAINABLE ENGINEERING AB

CETRI - CENTER FOR TECHNOLOGY RESEARCH & INNOVATION LTD

GOLINELLI - GOLINELLI GIULIO

EAAP - FEDERAZIONE EUROPEA PER LA ZOOTECNICA

EUREC - EUREC EESV

PUBLISHABLE SUMMARY

This inventory of best practices aims to provide livestock farmers with an overview of the most effective renewable energy solutions developed and tested in RES4LIVE, tailored to their specific operational needs. It covers a range of technologies including photovoltaic and solar thermal systems, biomethane production, and geothermal storage for heating, combined with efficient heat pumps and smart control approaches, each offering peculiar advantages depending on farm size, location, and energy requirements. By implementing these best practices, farms can reduce greenhouse gas emissions towards net-zero carbon, lower energy costs, and contribute to global efforts to combat climate change.

The inventory highlights not only the technical aspects of each renewable energy system but also key considerations for installation, maintenance, and economic feasibility. Through this guide, livestock farmers can make informed decisions that align with their sustainability goals while optimizing their energy efficiency. For each best practice, a summary and a table with technical data are normally provided. The summary is presented in a popular language, while the tables contain the main specialistic information.

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1 INTRODUCTION

1.1 Structure of the inventory

The agricultural sector, particularly livestock farming, faces increasing pressure to adopt sustainable practices that reduce environmental impact while maintaining productivity. Energy consumption is a significant component of farm operations, with livestock farms relying on electricity and heat for ventilation, lighting, water heating, and equipment use. Renewable energy technologies present a promising opportunity to meet these energy needs more sustainably and cost-effectively.

This inventory of best practices aims to provide livestock farmers with an overview of the most effective renewable energy solutions developed and tested in RES4LIVE, tailored to their specific operational needs. It covers a range of technologies including photovoltaic and solar thermal systems, biomethane production, and geothermal storage for heating, combined with efficient heat pumps and smart control approaches, each offering peculiar advantages depending on farm size, location, and energy requirements. By implementing these best practices, farms can reduce greenhouse gas emissions towards net-zero carbon, lower energy costs, and contribute to global efforts to combat climate change.

The inventory highlights not only the technical aspects of each renewable energy system but also key considerations for installation, maintenance, and economic feasibility. Through this guide, livestock farmers can make informed decisions that align with their sustainability goals while optimizing their energy efficiency. For each best practice, a summary and a table with technical data are normally provided. The summary is presented in a popular language, while the tables contain the main specialistic information.

1.2 Ranking criteria

The integration of renewable energy systems in livestock farms represents a significant opportunity to address the dual challenges of energy consumption and environmental sustainability. Livestock operations are energy-intensive, requiring power for heating, cooling, lighting, and various mechanized processes. Renewable energy technologies—such as solar panels, wind turbines, biogas digesters, and biomass systems—offer a way to reduce dependence on conventional energy sources, lower greenhouse gas emissions, and enhance farm resilience.

A SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) represents an effective tool for evaluating various best practices in renewable energy production, based on a qualitative approach that complements the quantitative information provided by the technical data reported for the various best practices.

The SWOT analysis is particularly effective when:

- **Assessing an overall strategic landscape**: SWOT is useful for understanding the competitive environment, market dynamics, and external opportunities or threats that could influence the choice of renewable energy technologies.

- **Considering hard-to-quantify variables**: Factors such as social acceptance, regulatory frameworks, and future opportunities driven by technological trends are challenging to evaluate with objective scores but can be easily explored in a SWOT analysis.
- **Focusing on a single case or project**: When evaluating technologies in a specific local context, the SWOT method highlights internal strengths and external factors without needing to delve into technical or numerical details.

1.2.1 SWOT Structure for Best Practices in Renewable Energy

A SWOT analysis helps identify strengths, weaknesses, opportunities, and threats for each best practice technology:

Strengths

- **Energy efficiency**: Ability to produce energy consistently or in abundance (e.g., solar in sunny regions).
- **Low operational costs**: Once installed, the technology might require minimal maintenance.
- **Mature technology**: Technologies that are well-established and have been widely tested and implemented (e.g., hydropower or photovoltaic solar energy).
- **Low environmental impact**: Technologies with minimal ecological footprint, like solar, compared to those with higher ecosystem impacts (e.g., biomass or large hydroelectric plants).

Weaknesses

- **High initial costs**: Technologies with high installation costs, such as wind or solar in challenging contexts.
- **Production variability**: Some technologies depend on natural factors (e.g., solar energy is intermittent and limited by sunlight).
- **Environmental or social impact**: Certain installations (like hydroelectric dams) can significantly affect ecosystems and local communities.
- **Emerging technologies**: Some technologies may be less reliable due to their early development stage (e.g., advanced biomass or shallow geothermal energy).

Opportunities

- **Government incentives**: Availability of subsidies, grants, or favourable policies that promote specific technologies.
- **Technological innovations**: Future improvements in technology could reduce costs or increase efficiency (e.g., energy storage solutions).

- **Growing market demand**: Increasing demand for green energy from consumers or industries may drive the adoption of certain technologies.
- **New geographical markets**: Expansion into areas where renewable resources are still underutilized.

Threats

- **Competition between technologies**: The advancement of one technology (e.g., offshore wind) might challenge other less efficient or more costly options (such as solar in areas with less sunlight).
- **Unfavourable regulation**: Changes in laws or policies may make a technology less attractive (e.g., restrictions on biomass or hydropower).
- **Social or cultural obstacles**: Resistance from local communities, such as opposition to wind farms or large solar installations.
- **Limited resources**: Scarcity of natural resources needed for energy production (e.g., land for large solar plants or water for hydropower).

1.2.2 Features of a SWOT Analysis

- **Broad overview**: When the goal is to get a comprehensive view of the strengths and weaknesses of a range of technologies and how they position themselves in the market or social environment.
- **Uncertain or emerging context**: In cases where quantitative analysis is difficult, or data is insufficient.
- **Strategic decision-making processes**: When the focus is on strategic planning, such as investing or developing public policies in emerging renewable energy sectors.

A SWOT analysis can be a great complement to a multi-criteria approach. It provides a qualitative evaluation of best practices in renewable energy production, focusing on internal strengths and weaknesses, as well as external opportunities and threats. However, for precise decisions based on numerical data, a quantitative approach like AHP or MCDM remains essential. Ideally, both approaches could be used together to provide a complete and robust understanding of the situation.

This SWOT analysis aims to evaluate the strengths, weaknesses, opportunities, and threats associated with implementing renewable energy systems in livestock farms. By examining internal factors (such as the farm's capacity to adopt these technologies) and external influences (like market trends and regulatory changes), this analysis provides insights into the potential benefits and challenges of transitioning livestock farms to renewable energy solutions. Understanding these dynamics is crucial for maximizing energy efficiency, sustainability, and long-term profitability in the livestock sector.

2 BEST PRACTICES OF RES4LIVE TECHNOLOGIES

The presentation of each best practice has been provided according to the test results and their processing (Tasks 4.3, 5.1), the case studies (Task 6.3), the co-design (Task 6.2), and economic and environmental evaluations (Tasks 5.2, 5.3).

2.1 Best practices of solar plants

2.1.1 Best practices of PVT systems for swine farms

Summary

Intensive livestock farming consumes a considerable amount of thermal and electrical energy. Therefore, Photovoltaic thermal (PVT) collectors, that convert solar radiation into usable thermal and electrical energy are an ideal source of renewable and carbon-free energy source for agriculture and livestock farming specifically. The average thermal output over the year is about 0.45 $MWhm^{-2}$ referred to as solar panel area, with the summer output being much higher than the winter one. The average electrical output over the year is about 0.1 $MWhm^{-2}$. This is an example of conditions in Northern Europe. In summer, a swine farm can be self-sufficient with solar alone depending on the heat demand and number of panels installed.

Specifically, for swine farms, they require heating all year round to keep the piglets around 34-38°C for newborn piglets, 24-35°C for piglets in the farrowing compartments, and 17-29°C in nursery rooms. Therefore, a considerable amount of heat is needed, even in summer. A heat storage tank can be used to store excess heat during the day for use at night, which can then provide space heating during the night for the piglets. In locations where it is beneficial, geothermal borehole seasonal storage can also be used, where the heat from the summer can be stored for the winter. Additionally, pairing solar thermal or PVTs with a heat pump has been shown to be greatly advantageous making the heat pump more efficient and harnessing the electricity produced from the PVTs to supply the heat pump. The COP of heat pumps in combination with solar thermal can be 2x more or even higher depending on temperatures. Using PVT technology has shown that payback times can be around 3-8 years depending on the availability of subsidies and the amount of solar installed. For a lifetime of 25 years with less maintenance requirements than a gas boiler, this is also a very economical solution.

Technical Data

Table 1: Main technical data of the installed PVT systems for swine farms.

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Average annual Thermal output	0.45	$MWhm^{-2}$	The peak thermal power of a PVT is usually $500W/m^2$

	Average annual Electrical output	0.1	MWhm^{-2}	The peak electrical power of a PVT is usually 170W/m^2
	Total efficiency	50-75	%	Energy harnessed from the sun. Depending on the working temperature and solar irradiance
Socio-economic parameters	Usual Payback time	3-8	Years	Depending on the price and amount of government subsidies
ILVO pilot farm				
Environmental Parameters	Effect of technology input on resource use due to fossil fuel consumption	1.745 [a]	% to the total difference [b] in the relevant indicator (measured in MJ / kg finished pig at the farm gate)	Mainly depending on the manufacturing of technology and on the modification (reduction) in natural gas input (used for heating the various barn compartments)
	Benefit in the resource use due to fossil fuel consumption	512.2	GJ/year	After the combined operation of the PVT and HP; allocated to finished pigs (the main product output of the farm)
	Effect of technology input on GHG emissions responsible for climate change	0.867 [a]	% to the total difference [b] in the relevant indicator (measured in kg CO$_2$eq / kg finished pig at the farm gate)	Mainly depending on the manufacturing of technology and the modification of on-farm greenhouse gas emissions after the reduction in natural gas input
	Benefit in the GHG emissions responsible for climate change	74.5	tn CO$_2$eq/year	After the combined operation of the PVT and HP; allocated to finished pigs (the main product output of the farm)
Golinelli pilot farm				
Environmental parameters	Effect of technology input on resource use due to fossil fuel consumption	1.682 [a]	% to the total difference [b] in the relevant indicator (measured in MJ / kg	Mainly depending on the manufacturing of technology and on the modification (reduction) in liquefied petroleum gas (LPG) input (used for heating the nursery barn)

			weaned piglets at nursery barn gate)	
	Benefit in the resource use due to fossil fuel consumption	497.2	GJ/year	After the combined operation of the PVT, HP and BTES systems
	Effect of technology input on GHG emissions responsible for climate change	1.475 [a]	% to the total difference [b] in the relevant indicator (measured in kg CO_2eq / kg weaned piglets at the nursery barn gate)	Mainly depending on the manufacturing of technology and the modification of greenhouse gas emissions from the nursery barn after the reduction in LPG input
	Benefit in the GHG emissions responsible for climate change	34	tn CO_2eq/year	After the combined operation of the PVT, HP and BTES systems

[a] The technology input has an increasing effect on the environmental impact indicator, while the combined effect of all technologies (i.e. input and operation) in the first year of operation is decreasing.

[b] The difference refers to the scenarios before the installation of the technologies and after one year of operation of the technologies

2.1.2 Best practices of PVT systems for cattle farms

Summary

Intensive livestock farming consumes a considerable amount of thermal and electrical energy. Therefore, Photovoltaic thermal (PVT) collectors, that convert solar radiation into usable thermal and electrical energy are an ideal source of renewable and carbon-free energy source for agriculture and livestock farming specifically. The average thermal output over the year is about 0.45MWhm^{-2} referred to as solar panel area, with the summer being much higher than the winter. The average electrical output over the year is about 0.1MWhm^{-2}. This is an example of conditions in Northern Europe. In summer, a cattle farm can easily be self-sufficient with solar alone depending on the heat demand and number of panels installed.

In dairy farms specifically, heat is only used for cleaning the barn, the milk tanks, and the automatic milking systems. Therefore, the heat required is usually at a high temperature, around 60-70°C or even more. It is advisable to use higher temperature solar thermal collectors to preheat the heat before an e-boiler takes the heat to the desired temperature. Farms with automatic milking systems must ensure that preheated water can be input into the system as these systems mostly have their own way of heating the water. Even if it is not possible to integrate solar thermal with the automatic milking system, solar thermal can be used for domestic hot water and cleaning of the barn and tanks. In this case, not as many panels are needed. Some cattle farms are equipped with milk storage, where heat can be recovered from the milk chillers to pre-heat water for domestic hot water use. If this system is available on the cattle farm, then it must be made sure that the collectors are performant enough to be able to further increase this heat without any risk of overheating the solar system.

A heat storage tank can be used to store excess heat during the day for use at night, and also contain excess heat generated during the day. Additionally, pairing solar thermal or PVTs with a heat pump has been shown to be greatly advantageous making the heat pump more efficient and harnessing the electricity produced from the PVTs to supply the heat pump. The COP of heat pumps in combination with solar thermal can be 2x more or even higher depending on temperatures. Using PVT technology has shown that payback times can be around 2-6 years depending on the availability of subsidies and the amount of solar installed. The payback can be estimated as lower than swine farms as the heat demand is not as much. However, the higher temperatures may contribute to higher costs for the solar system overall. For a lifetime of 25 years with less maintenance requirements than a gas boiler, this is also a very economical solution.

Technical Data

Table 2: Main technical data of the installed PVT systems for cattle farms.

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Average annual Thermal output	0.45	$MWhm^{-2}$	The peak thermal power of a PVT is usually $500W/m^2$
	Average annual Electrical output	0.1	$MWhm^{-2}$	The peak electrical power of a PVT is usually $170W/m^2$
	Total efficiency	50-75	%	Energy harnessed from the sun. Depending on the working temperature and solar irradiance
Socio-economic parameters	Usual Payback time	3-8	Years	Depending on the price and amount of government subsidies
Environmental Parameters	Effect of technology input on resource use due to fossil fuel consumption	8.88 [a]	% to the total difference [b] in the relevant indicator (measured in MJ / kWh of heat	Mainly depending on the manufacturing of technology and the reduction in the electricity consumption in the electric boiler

			produced by the electric boiler)	
	Benefit in the resource use due to fossil fuel consumption	65.4	GJ/year	After the operation of the PVT system
	Effect of technology input on GHG emissions responsible for climate change	11.693 [a]	% to the total difference [b] in the relevant indicator (measured in kg CO_2eq / kWh of heat produced by the electric boiler)	Mainly depending on the manufacturing of technology and the reduction in the electricity consumption in the electric boiler
	Benefit in the GHG emissions responsible for climate change	4.12	tn CO_2eq/year	After the operation of the PVT system

[a] The technology input has an increasing effect on the environmental impact indicator, while its total effect (i.e. due to input and operation) in the first year of operation is decreasing.

[b] The difference refers to the scenarios before the installation of the technology and after one year of operation of the technology

2.1.3 Best practices of PVT systems installation

Photovoltaic (PV) and solar thermal technology have been available, and mass-produced for decades, with a very experienced understanding among experts and installers. Solar thermal installations are slightly more complex than PV as they involve a pumped fluid and thermal management. It is, however, not more complicated than a residential heating system. On the other hand, it is also 3 times more efficient than PV and will require about 3 to 4 times fewer panels to deliver the same amount of energy.

Due to this complexity, solar thermal has not gained as much popularity compared to PV in the last years. It is therefore important to hire solar installers or plumbers that have experience with solar thermal installations and can react when an issue or overheating occurs. It is also advisable to install a sufficiently big enough heat storage tank for the occasional very sunny day and have a small buffer for when the heat demand is not as much as usual. This is to prevent overheating. Another approach is to install a heat dump valve or heat dump fan to dissipate excess heat in emergencies when the system is too hot. A solar system is generally sized to provide 100% of the heating needs of the site during the summer unless seasonal heat storage and batteries are available to store summer energy for use in winter. In the winter and cooler months, a secondary heat source is needed to top up the necessary heat.

Solar thermal system requires very little maintenance, comparable to the annual gas boiler service. It is advisable to deaerate the solar thermal system annually, check the pressure, and any leaks, and check it has not overheated. It is a simple procedure that will ensure the system will work for at least 20-40 years.

2.1.4 Best practices of PV systems for poultry farms

Photovoltaic (PV) systems are becoming increasingly popular on poultry farms due to their potential to reduce energy costs and environmental impact. When implementing a PV system on a poultry farm, several best practices should be followed to ensure optimal performance and return on investment.

The first consideration is the design and sizing of the system. It’s crucial to accurately assess the farm’s energy needs, which are typically high due to continuous operations like lighting, ventilation, heating, and cooling. By analyzing historical energy consumption data, the system can be sized to meet these demands effectively. Proper placement of the panels to maximize sunlight exposure, typically on rooftops or open fields with minimal shading, is also vital. The orientation and tilt angle of the panels should be optimized to capture the maximum amount of solar energy.

Another key factor is the cost and payback period of the system. While the initial investment can be significant, the long-term savings can be substantial. The payback period, or the time it takes for energy savings to cover the initial investment, depends on factors such as local electricity rates, available incentives, and the specific energy consumption patterns of the farm. Once the system is paid off, the farm benefits from essentially free electricity for the remainder of the system’s lifespan.

Net-metering and storage are also important considerations. The first option allows the farm to sell excess electricity generated by the PV system back to the grid, effectively reducing electricity bills. This is particularly beneficial during peak sunlight hours when the system may produce more energy than the farm consumes. Energy storage systems, such as batteries, can store this excess energy for use during non-sunny periods, like nighttime or cloudy days, providing greater energy security and reducing dependence on grid electricity. Although adding storage increases the initial cost of the system, it can help avoid peak electricity rates, ensure a consistent energy supply, which is particularly valuable for operations that run 24/7, and follow the specific energy consumption patterns of the farm.

Lastly, integrating the PV system with other renewable energy systems (RES), such as heat pumps (see section below), can further enhance energy efficiency and sustainability. For instance, combining PV with wind energy can provide a more reliable power supply by balancing the intermittent nature of solar power with wind energy, especially during night-time or cloudy periods. Biogas systems, which convert poultry waste into energy, can provide a continuous energy source, complementing the PV system and enhancing the farm’s overall energy resilience. This integration not only improves sustainability but also turns waste management into an additional energy resource, further reducing the farm’s carbon footprint.

By following these best practices, poultry farms can implement PV systems that are cost-effective, reliable, and environmentally friendly, ensuring long-term sustainability and profitability. The main technical data of the system installed in the AUA poultry farm are provided in Technical Data
Table 3 below. This particular design and installation were of course constrained by space limitations in the AUA farm.

Technical Data

Table 3: Main technical data of the installed PV system in AUA.

Parameter	**Performance parameter**	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Installed capacity	9.00	kWp	20 PV panels of 450 Wp
	Slope	20 (approx.)	[°]	Fixed mounting
	Azimuth	-40 (approx.)	[°]	
	Conversion efficiency	10.04%	-	The ratio of energy production to solar energy incident on PV panel surface, in the range 9.90 - 13.66%
	Energy production	7,970.90	kWh	Annual
Socio-economic parameters	Initial investment	6,600.00	€	Purchase and installation
	Maintenance costs	300.00	€	Annually
Environmental parameters	Effect of technology input on resource use due to fossil fuel consumption	5.39[a]	% to the total difference [b] in the relevant indicator (measured in MJ / kg of egg at the farm gate)	Mainly depending on the manufacturing of technology and the reduction in the electricity consumption in the facility.
	Benefit in the resource use due to fossil fuel consumption	- 2.94[c]	GJ/year	Annual, after the operation of the PV panels
	Effect of technology input on GHG emissions responsible for climate change	7.01	% to the total difference [b] in the relevant indicator (measured in	Mainly depending on the manufacturing of technology and the reduction in the

			kg CO_2eq / kg of egg at the farm gate)	electricity consumption in the facility.
	Benefit in the GHG emissions responsible for climate change	5.1	tn CO_2-eq / year	Annual, after the operation of the PV panels

[a] The technology input has an increasing effect on the environmental impact indicator. The potential decrease depends on the combined effect of all technologies (i.e. input and operation).

[b] The difference refers to the scenarios before the installation of the technology and after one year of operation of the technology

[c] In this case, we have a negative effect. This is the result of the higher energy consumption of the facility.

2.2 Best practices of heat pumps

2.2.1 Best practices for heat pumps installation

Summary

When installing heat pumps, especially multi-source systems, it's crucial to ensure that the design and placement are correct from the beginning. A thorough assessment of the farm's heating and cooling needs is a prerequisite, considering factors like building insulation, climate, and the specific requirements of the animals. Proper sizing is essential; an undersized heat pump will struggle to maintain the desired temperature, while an oversized system will cycle on and off frequently, reducing efficiency and lifespan. Location matters too, so the heat pump should be placed in an area where it can easily access the energy sources it needs, like the ground, air, or water. Ensure the system is installed by a qualified professional who follows local codes and manufacturer guidelines. Proper installation and maintenance not only maximize efficiency but also prevent issues like noise, vibrations, and unnecessary wear and tear.

2.2.2 Best practices for using multi-source heat pumps in heating swine farms and controlling the environment in poultry houses

Summary

Multi-source heat pumps (HP) have been established on the market and can emerge as a critical technology in modern agriculture; particularly in swine and poultry farming, where efficient heating and environmental control are essential for maintaining animal welfare and optimizing production. The adoption of these systems is growing, driven by their ability to utilize multiple energy sources such as air, water, and ground, thereby increasing flexibility and efficiency. When designing and sizing heat pumps for swine farms and poultry houses, it is essential to consider the unique thermal demands of these environments. Swine farms, for example, require consistent and reliable heating, particularly during the colder months, to ensure that piglets are kept warm. In contrast, poultry houses demand a more dynamic approach, with heating, cooling, and ventilation all playing crucial roles in maintaining an optimal environment for bird health and productivity. To accurately size a multi-source heat pump system, one must conduct a detailed analysis of the farm's heating and cooling load requirements, considering factors such as building insulation, local climate, and the thermal mass of the structures. The preferred managerial practices have also to be taken into consideration for their proper integration. A well-designed system should be capable of meeting peak demand without oversizing, which would lead to higher upfront costs and reduced efficiency.

Cost and payback periods are critical considerations for farmers when deciding to implement multi-source heat pumps. While the initial investment can be substantial, especially when compared to traditional heating systems like gas or oil boilers, the long-term savings in energy costs often justify the expense. In swine farms, where heating represents a significant portion of operational costs, a well-designed heat pump system can reduce energy consumption, leading to a reasonable payback period depending on the size of the installation, local energy prices, and available subsidies or incentives. For poultry houses, the payback period may vary, but the integration of cooling and ventilation functions into the heat pump system can further enhance cost-effectiveness, as it reduces the need for separate systems. It's also worth noting that multi-source heat pumps can be more cost-effective in the long run because they can switch between different energy sources depending on which is most efficient at any given time, thus optimizing operational costs.

The Seasonal Coefficient of Performance (SCOP) is a key metric for evaluating the efficiency of heat pumps across different seasons. For multi-source heat pumps, SCOP values are typically higher than those of single-source systems because they can optimize their performance by switching to the most efficient energy source available at the time. For instance, in a swine farm during winter, a heat pump might draw heat from the ground, which maintains a relatively stable temperature compared to the outside air, thereby improving efficiency. In the summer, the same system might switch to air or water sources to provide cooling in a poultry house, again optimizing efficiency. A high SCOP not only translates to lower energy bills but also contributes to the sustainability of the farming operation by reducing its carbon footprint.

Integration with other renewable energy systems (RES) is another best practice that can significantly enhance the performance and sustainability of multi-source heat pumps. For example, pairing a heat pump system with solar photovoltaic (PV) panels can provide a renewable source of electricity to power the heat pump, further reducing energy costs and improving the environmental footprint of the farm. Similarly, integrating the heat pump with combined heat and power (CHP) or waste heat recovery (WHR) systems, the electricity or heat that can be used by the heat pump, thus creating a closed-loop system where waste is converted into valuable energy. Such integrations not only make the farming operation more self-sufficient but also protect against fluctuations in energy prices and supply disruptions.

The adoption of multi-source heat pumps in swine and poultry farming represents a forward-thinking approach to energy management that can offer an attractive option for farmers looking to modernize their operations. With proper design, implementation, and integration, these systems can provide a reliable, cost-effective, and sustainable solution for heating swine farms and controlling the environment in poultry houses, ultimately leading to improved animal welfare and increased profitability.

Technical Data

Table 4: Main technical data of the installed Low- and High-Temperature Heat Pumps in ILVO swine farm.

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Cooling capacity	20.00 / 28.20	kW	Low / High
	Heating capacity	24.53 / 39.50	kW	
	Power	4.50 / 11.35	kW	
	Nominal COP	4.45 / 2.48	-	
Socio-economic parameters	Initial investment	74,300.00	€	Purchase and installation
	Maintenance costs	1000.00	€	Annually
Environmental parameters	Refrigerant	R407C	-	
	Effect of technology input on resource use due to fossil fuel consumption.	0.332 [a]	% to the total difference [b] in the relevant indicator (measured in MJ / kg finished pig at the farm gate)	Mainly depending on the manufacturing of technology and on the modification (reduction) in natural gas input (used for heating the various barn compartments)
	Benefit in the resource use due to fossil fuel consumption	512.2	GJ/year	After the combined operation of the PVT and HP
	Effect of technology input on climate change	0.002 [a]	% to the total difference [b] in the relevant indicator (measured in kg CO_2eq / kg finished pig at the farm gate)	Mainly depending on the manufacturing of technology and the modification of on-farm greenhouse gas emissions after the reduction in natural gas input
	Benefit in the GHG emissions responsible for climate change	74.5	tn CO_2eq/year	After the combined operation of the PVT and HP

[a] The technology input has an increasing effect on the environmental impact indicator, while the combined effect of all technologies (i.e. input and operation) in the first year of operation is decreasing.

[b] The difference refers to the scenarios before the installation of the technologies and after one year of operation of the technologies

Technical Data

Table 5: Main technical data of the installed Heat Pump in GOLINELLI swine farm.

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Cooling capacity	44.6	kW	
	Heating capacity	35.10	kW	
	Power	10.05	kW	
	Nominal COP	3.49	-	
Socio-economic parameters	Initial investment	46,200.00	€	Purchase and installation
	Maintenance costs	1000.00	€	Annually
Environmental parameters	Refrigerant	R407C	-	
	Effect of technology input on resource use due to fossil fuel consumption	0.253[a]	% to the total difference in the relevant indicator (measured in MJ / kg weaned piglets at the nursery barn gate) [b]	Mainly depending on the manufacturing of technology and on the modification (reduction) in liquefied petroleum gas (LPG) input (used for heating the nursery barn)
	Benefit in the resource use due to fossil fuel consumption	497	GJ/year	After the combined operation of the PVT, HP and BTES systems
	Effect of technology input on GHG emissions	0.218 [a]	% to the total difference in the	Mainly depending on the manufacturing of technology and the modification of greenhouse gas emissions

	responsible for climate change		relevant indicator (measured in kg CO_2eq /kg weaned piglets at the nursery barn gate) [b]	from the nursery barn after the reduction in LPG input
	Benefit in the GHG emissions responsible for climate change	34	tn CO_2eq/year	After the combined operation of the PVT, HP and BTES systems

[a] The technology input has an increasing effect on the environmental impact indicator, while the combined effect of all technologies (i.e. input and operation) in the first year of operation is decreasing.

[b] The difference refers to the scenarios before the installation of the technologies and after one year of operation of the technologies

Technical Data

Table 6: Main technical data of the installed Heat pump in AUA poultry farm.

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Cooling capacity	9.28	kW	
	Heating capacity	12.19	kW	
	Power	2.91	kW	
	Nominal COP	3.19	-	
Socio-economic parameters	Initial investment	45,000.00	€	Purchase and installation
	Maintenance costs	700.00	€	Annually
Environmental parameters	Refrigerant	R407C	-	
	Effect of technology input on resource use due to fossil fuel consumption	5.12[a]	% to the total difference [b] in the relevant indicator (measured in MJ / kg of egg	Mainly depending on the manufacturing of technology and the reduction in the electricity

			at the farm gate)	consumption in the facility.
	Benefit in the resource use due to fossil fuel consumption	- 2.79[c]	GJ/year	Annual, after the operation of the PV panels and the HP.
	Effect of technology input on GHG emissions responsible for climate change	7.13[a]	% to the total difference [b] in the relevant indicator (measured in kg CO_2eq / kg of egg at the farm gate)	Mainly depending on the manufacturing of technology and the reduction in the electricity consumption in the facility.
	Benefit in the GHG emissions responsible for climate change	- 0.24[c]	tn CO_2-eq / year	Annual, after the operation of the PV panels and the HP.

[a] The technology input has an increasing effect on the environmental impact indicator. The potential decrease depends on the combined effect of all technologies (i.e. input and operation).

[b] The difference refers to the scenarios before the installation of the technology and after one year of operation of the technology

[c] In this case, we have a negative effect. This is the result of the higher energy consumption of the HVAC (Heating, Ventilation and Air Conditioning) system.

2.2.3 Best practices of geothermal storage (BTES)

Summary

Borehole Thermal Energy Storage (BTES) for livestock structures allows the exploitation of available but not immediately usable heat sources, commonly present in farms, as an alternative to the use of fossil fuels. It consists of a field of geothermal probes of variable depth and number, to be defined on the basis of the characteristics of the ground. The hot fluid from the heat source to be stored, which can be, for example, a solar panel system or a biogas cogeneration system, is circulated in the BTES field and the thermal conduction between the fluid and the ground, through the pipes, leads to an increase in the subsoil temperature, especially in the centre of the BTES field, its thermal core. The main areas of direct application are livestock farms, especially those in alluvial plains, characterized by the need for considerable heat and the availability of large areas for installing the BTES (drilling and excavation). Seasonal heat storage is environmentally beneficial because it can enable carbon neutrality; it is also economically and logistically advantageous since it contributes to the energy independence of farms.

Technical Data

Table 7: Main technical data of the installed geothermal storage (BTES).

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Storage capacity of solar thermal energy	40%		(Ratio of the solar radiant energy over the PVT area to the heat stored underground) 8 BHEs of 30 m depth coupled with a PVT plant of 25 kW_{th}
	Maximum injectable temperature	35	°C	Safety in order not to damage the plastic pipes and for environmental protection of the aquifer
	Minimum temperature in the BTES	-2	°C	Using glycol during the heat extraction with DHSP
	Temperature increase of the ground due to storage	5	K	In Golinelli, approximately ground temperature rises from 15 (natural state) to 20°C (after a season of heat injection).
	Max heat extraction capacity	26.8	kW	8 BHEs of 30 m depth, providing peak power to the DSHP 34 kW, after summer heat injection, with peak COP = 4.7. No use of air.
	Average heat extraction capacity	13	kW	8 BHEs of 30 m depth providing average power to the DSHP 34 kW, in the middle of winter and using glycol, exploiting half of the power (17 kW)

				with peak COP = 4.7. The remaining power is provided by hybrid use with air, reducing the total COP to 4.3
	Standard temperature difference between inlet and outlet during extraction	3	K	
	Standard temperature difference between inlet and outlet during injection	5	K	
Environmental parameters	CO2 saving yearly	8621	kg CO_2eq	Assessed according to computation criteria described by Murali et al. (2024)[a], on the basis of the average irradiance of the site.
	Effect of technology input on resource use due to fossil fuel consumption	0.279 [b]	% to the total difference [c] in the relevant indicator (measured in MJ / kg weaned piglets at nursery barn gate)	Mainly depending on the manufacturing of technology and on the modification (reduction) in liquefied petroleum gas (LPG) input (used for heating the nursery barn)
	Benefit in the resource use due to fossil fuel consumption	497	GJ/year	After the combined operation of the PVT, HP and BTES systems
	Effect of technology input on GHG emissions responsible for climate change	0.213 [b]	% to the total difference [c] in the relevant indicator (measured in kg CO_2eq / kg weaned piglets at the nursery barn gate)	Mainly depending on the manufacturing of technology and the modification of greenhouse gas emissions from the nursery barn after the reduction in LPG input

	Benefit in the GHG emissions responsible for climate change	34	tn CO_2eq/year	After the combined operation of the PVT, HP and BTES systems

[a] *Murali, D., Acosta-Pazmiño, I.P., Loris, A., García, A.C., Benni, S., Tinti, F., Gomes, J. Experimental assessment of a solar photovoltaic-thermal system in a livestock farm in Italy (2024) Solar Energy Advances, 4, art. no. 100051. DOI: 10.1016/j.seja.2024.100051*

[b] *The technology input has an increasing effect on the environmental impact indicator, while the combined effect of all technologies (i.e. input and operation) in the first year of operation is decreasing.*

[c] *The difference refers to the scenarios before the installation of the technologies and after one year of operation of the technologies*

2.3 Best practices of biomethane plant

2.3.1 Best practice of on-farm production and upgrading of biogas to biomethane and BioCNG fuel

The production of biogas on livestock farms using field and on-farm residues, manure and slurry represents a multifaceted option for fossil-free energy production. The most common variant is the conversion of raw biogas resulting from anaerobic digestion into heat and electricity in a combined heat and power plant (CHP). Plant sizes between 100 kW_{el} and 250 kW_{el} are economically feasible in practice. Another possible use of raw biogas is its purification into biomethane and then high compression to 250 bar for use as a BioCNG fuel. Vehicles then can be refuelled from the gas storage without the need for additional pumps by using the pressure differences until pressure balance is achieved.

A single-stage membrane purification process with the return of the separated CO_2 to the digester next to the CHP allows using about 10 to 20 % of the total volume flow of raw biogas for CNG fuel, which results in a CH_4 reduction in the remaining raw gas stream for the CHP.

Taking a biogas plant with 200 kW_{el} as an example, this corresponds to a raw biogas volume of 100 $Nm^3\ h^{-1}$. The dimensioning of the biomethane upgrading plant needs to fit the biogas production. An upgrading plant with a gas purification performance between 10 and 35 $Nm^3\ h^{-1}$ with subsequent high compression to BioCNG that can work off the natural gas grid is available on the market for the first time within this RES4LIVE project can economically convert 10 to 20 % of the raw biogas from the small biogas plants (100-250 kW) typical for livestock farms to BioCNG fuel.

A full cost calculation for operating a 35 $Nm^3\ h^{-1}$ biogas to BioCNG plant at a capacity of 70 % results in producing BioCNG at a fuel cost of 1.51 € kg^{-1}. Any monetary benefits from GHG quotas from the production and use of biofuel have not yet been taken into account and can have an additional positive effect. A key item here is the working load of at least 70 % for the upgrade plant. Since the upgrade plant is supposed to work off-grid, it is required to provide adequate storage capacity as well as continuous and consistent usage of the BioCNG. If the BioCNG is unlikely to be completely utilized on the farm, potential external commercial customers should be considered in a business plan. Biomethane is an interesting option for fossil-free mobility, especially for use in heavy-duty vehicles like tractors or trucks, as the electrically powered alternatives are comparatively uncompetitive in terms of performance parameters.

Some key figures may be useful to illustrate the potential for defossilizing agriculture (or forestry). The manure of one cow provides about 289 Nm³ a^{-1} biomethane, which can be upgraded to 208 kg a^{-1} BioCNG – enough to plough 8 ha with a rotary plough or to go 4,000 km with a car. Similarly, 1 t of wheat straw provides about 250 Nm³ biomethane that can be upgraded to 180 kg BioCNG, allowing 7 ha of ploughing work or going 3,600 km with a car.

Technical Data

Table 8: Main technical data for the biomethane to BioCNG upgrade plant.

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Biomethane upgrade plant with 35 Nm³ h^{-1} upgrade capacity				
Physical parameters	Operational time over a year	70-95 or 6,132 – 8,322	% h	This range of operation time allows economic feasibility.
	Energy consumption	12.2	kW	The energy required for the compressor block
	BioCNG production	54,574.8	kg a^{-1}	Value applies to operation at 70 % capacity
	CH_4 content in BioCNG	94 - 98	%	
	CNG storage pressure	220 - 250	bar	
Environmental parameters	Fossil fuel (diesel) replacement potential	54,574.8 – 68,218.5	L a^{-1}	Depending on engine efficiency, 1 kg of BioCNG can replace between 1 and 1.25 L of diesel.
	Fossil CO_2 saving potential	120,610.31 – 150,762.89	kg a^{-1}	Replacing 1 – 1.25 L diesel with 1 kg BioCNG saves between 2.21

				and 2.76 kg of fossil CO_2
Biomethane upgrade plant with 10 Nm³ h⁻¹ upgrade capacity [a]				
	Effect of technology input on resource use due to fossil fuel consumption	1.08 [b]	% to the total indicator value [c] (measured in MJ / m^3 biomethane produced at the gate of the unit installed)	Mainly depending on the manufacturing of technology
	Benefit in the resource use due to fossil fuel consumption	638.3	GJ/year	Due to the potential replacement of diesel fuel caused by the operation of the installed unit and the avoidance of its production
	Effect of technology input on GHG emissions responsible for climate change	2.51 [b]	% to the total indicator value [c] (measured in kg CO_2eq / m^3 biomethane produced at the gate of the unit installed)	Mainly depending on the manufacturing of technology
	Benefit in the GHG emissions responsible for climate change	11	tn CO_2eq/year	Due to the potential replacement of diesel fuel caused by the operation of the installed unit and the avoidance of its production

[a] *The results derive from the Environmental Life Cycle Assessment (eLCA) of the BioCNG unit developed in the framework of RES4LIVE and installed at the LVAT pilot farm.*

[b] *The technology input has an increasing effect on the environmental impact indicator.*

[c] *The total indicator value refers to the annual performance of operating the BioCNG unit at LVAT.*

2.3.2 Best practices of adaptation of a farm tractor for biomethane use

Summary

The retrofitting of diesel farm tractors for biomethane allows for the displacement of the use of fossil diesel fuel with a renewable fuel to lower the GHG on the entire operation of the tractor. It is an economical option combined with a small upgrading station of biogas to biomethane when biogas is available at the farm or nearby. It consists of adding tanks to store the biomethane onboard the tractor and changing its combustion by removing the diesel pump and injectors to replace them with spark plugs, ignition coils, and gas injectors controlled by an electronic unit (ECU). It requires the machining of the cylinder head and the pistons as well as a check of the good operation of the turbocharger. This can be developed as a retrofit kit.

Indeed, diesel farm tractors can have a long lifetime exceeding 20 years, which makes them high emitters of pollutants and CO_2 even if their daily usage is limited. RES4LIVE demonstrated that those tractors can be converted (retrofitted) to operate with biomethane as described above. But for a successful conversion, several criteria must be present to fit the retrofit kit, the first being the availability of biomethane conveniently and at a competitive price, the second being the price of the retrofit kit and the last an educated service network to take care of the maintenance of the tractor.

The biomethane is stored as compressed gases up to 200 bar onboard the tractor. This makes it possible to obtain about the equivalent of 30 liters of diesel which typically allows 3 to 4 hours of operation for a farm tractor (about 60 to 80kW). If more biogas fuel (biomethane) is required onboard the tractor for special duty cycles, convenient refuelling must be organized, because more tanks onboard the tractor is not possible unless the tractor would lose functionalities because of the volume required by the gas tanks. Though, refuelling must be reachable easily, and the good point is that this phase is as fast as refuelling with diesel. At the same time, as the biomethane composition can affect the engine responsivity, the biomethane production and quality must be as constant as possible, which implies selecting a validated process to upgrade the biogas to biomethane.

The second point is the cost of the conversion of a farm tractor to biomethane. A cost of 50 % of the value of the tractor when it was new sounds the maximum acceptable. The only way to achieve this target is to produce a conversion kit which is compatible with different tractor models. The retrofit kit must also be certified, though no delay or possible extra cost would be hidden. For that, fair rules must be selected before exhaust emissions target as older diesel technology can be adapted for renewable fuel (biomethane) lowering the exhaust emissions but not at the same time to the latest emission standard of Non-Road Mobile Machinery (EU 2016/1628). This is a major point because the acceptability of the retrofit model can only be if the price is affordable, and aiming at the latest exhaust limits would just not be possible

The last point is a service network. The gas technology (biomethane) is robust if it is correctly engineered and can last for at least 15 years. But maintenance of the tractor will be required regardless of the reason, the retrofit kit or the other systems on the tractor. A service network with a large scope, including training the potential candidates, must be developed at the same time as the engineering work starts. The service network could also promote the sale of the conversion kits.

Technical Data

Table 9: Main technical data of the farm tractor adapted for biomethane use.

	Performance parameter	**Target value or range**	**Unit of meas.**	**Notes**
Physical parameters	Power	56 to 130	kW	Same as the diesel power (original before retrofit)
	Fuel consumption	6 to 8	kg of biomethane	Daily average
	Range	3 to 4	Hours	Daily average
	Biomethane quality (from biogas)	> 85	% CH4	Biomethane combustion is as stable as possible
Socio-economic parameters	Retrofit policy	Available	-	Qualified kit against regulation.
	Retrofit cost	30 000.00	€	Retrofit kit and installation labour. < 50% of the price of a new farm tractor of the same value. The tractor must be in a state where it will be run for an additional 15 years.
	Maintenance cost	300 - 500	€	Annually. Including leak detection tests.
	A specialized service workshop network (technical support)	30 (c.a.)	Km	The workshop must be trained to maintain vehicles or machines

				powered by biomethane and to handle cases which require removing the high-pressure gas components. The work must be carried out following the safety rules. The workshop technicians must be qualified to work on the farm site with the qualification to intervene in the gas components.
	Training and peer network	Available	-	When the retrofit kit is delivered. Performed at the farm where the tractor is being used. Workshop to share experience.
Environmental parameters	Biogas available	3 (c.a.)	km	At the farm or in the close neighbourhood.
	Exhaust emissions (NOx)	< 3.3	g/kWh	stage III B
	Exhaust emissions (Particulates)	< 0.025	g/kWh	stage III B

	Effect of technology input on resource use due to fossil fuel consumption	7.37 [a]	% to the total difference [b] in the relevant indicator (measured in MJ / h of tractor operation)	Mainly depending on the manufacturing of technology and the modification of the fuel used in the tractor (from fossil diesel to biomethane)
	Benefit in the resource use due to fossil fuel consumption	809.5	GJ/year	After the operation of the retrofitted tractor (max. of 5h of daily operation)
	Effect of technology input on GHG emissions responsible for climate change	30.7 [c]	% to the total difference [b] in the relevant indicator (measured in kg CO_2eq / h of tractor operation)	Mainly depending on the manufacturing of technology and the modification of the fuel used in the tractor (from fossil diesel to biomethane)
	Benefit in the GHG emissions responsible for climate change	-14.1	tn CO_2eq/year	After the operation of the retrofitted tractor (max. of 5h of daily operation)

[a] The technology input has an increasing effect on the environmental impact indicator, while the total effect (i.e. input and operation) in the first year of operation is decreasing.

[b] The difference refers to the scenarios before the retrofitting of the tractor and after one year of operation of the retrofitted tractor.

[c] Both the effects of technology input and the total effect (i.e. input and operation) on the environmental impact indicator in the first year of operation of the retrofitted tractor are increasing.

2.4 Best practice of smart control with sensors

2.4.1 Best practice of ventilation of livestock building

Summary

A tube ventilation system can be augmented with a cooling option by adding evaporative cooling pads that allow the mixing of pre-cooled air into the ambient air ventilation stream. In the case of dairy cows in the temperate climate zone ventilation can start at as early as 15 °C ambient temperature. Cooling can begin at 18 °C and reach the peak at 25 °C, where only pre-cooled air is injected into the ventilation tubes. Appropriate dimensioning of the whole system requires running computer simulations of the barn's climate. The number of tubes and cooling pads as well as the required performance of fans and pumps need to be based on this.

The coolers should have a permanent water supply, ideally with a direct connection to the water grid, to keep the pads wet during hot summer periods, they should be set up level to avoid water loss and keep moistening the pads efficiently. For easy maintenance, a clearly visible water level indicator should be available. The distance from cooling pads to the animals should be less than 10 m to minimize losses of cool air; otherwise, additional measures like using (better) insulated tubes are required.

The whole system requires sensors and a control unit to adjust the air conditioning over a wider range of ambient conditions to provide the best possible animal welfare. Sensors need to measure temperature and relative humidity as well as the rotational speed of the fans, while the control unit needs to regulate the mixing of ambient and pre-cooled air as well as the speed of the fans to provide an adequate volume flow rate inside the ventilation tubes, even if the system is not perfectly maintained.

Easy accessibility of important parts like pads, pipes, pumps, water reservoirs, filters and fans for easy cleaning and maintenance is also important. Livestock buildings often are prone to larger amounts of dust that can have negative effects like blocking water pipe openings, accumulating dirt in water reservoirs (potentially circulating dirty water on the cooling pads, thus reducing their effectiveness), adding weight to the airflow tubes, blocking of pumps and faster blocking of filters as well as possible malfunctions in sensors. Therefore, maintenance of all those parts should be as easy as possible, potentially with little or no need for tools. A barn management that is set up to avoid dust as much as possible will be beneficial for such a ventilation and cooling system.

In a barn designed for 54 cows, a system with three tubes (two at both long sides and a larger one in the centerline) and three corresponding cooling pads managed to drop barn temperature by a maximum of 5 K at ambient temperatures below 30 °C, as a proof of concept.

2.4.2 Best practices for heat pumps control

Once the heat pump is installed, effective control is essential for maximizing the system's effectiveness. Utilization of smart controls is used in order to automatically adjust the system based on real-time conditions, such as indoor and outdoor temperature fluctuations, or occupancy levels in the livestock farm. This ensures the system runs only when necessary to provide the necessary thermal loads, saving energy – while at the same time - extending the life of the heat pump and accompanying equipment. Seasonal adjustments are important too; the system should be set up to optimize performance based on the season, switching energy sources as needed to maintain efficiency. Integration with other renewable energy systems, like solar panels, can further enhance control, allowing the heat pump to operate on the most cost-effective and sustainable energy available. Regular remote monitoring of the key parameters, such as on/off cycles, refrigerant pressures and alarms, is also critical to ensure the system continues to run smoothly and efficiently over time.

A smart control system may include several modules, such as algorithms, data transmission modules, and a rule engine that combines data from various parameters and triggers actions based on specific conditions (e.g., high temperature combined with low humidity) to activate specific features and operational modes of the heat pump (e.g., heating, cooling, fan-only). Additionally, a smart control system may incorporate more advanced modules, such as weather prediction, to account for local microclimate forecasts and perform actions that further optimize heat pump operation and energy consumption.

Furthermore, a smart control module often provides additional functionalities beyond automation, such as remote control of the system through a user interface. This interface offers real-time and historical data on relevant parameters (e.g., temperature, carbon dioxide levels, humidity, energy consumption) and allows users to adjust the heat pump's operational mode and temperature setpoints. To prevent mistakes or malicious use, remote control is restricted to a subset of users with specific permissions.

Typically, the control system of a heat pump utilizes the Modbus protocol, which is the industry standard. However, if cabling installation is difficult or too costly, alternative solutions can be implemented, such as using adaptors to enable wireless communication and reduce costs.

3 RANKING OF BEST PRACTICES

This SWOT analysis evaluates the strengths, weaknesses, opportunities, and threats of different renewable energy systems—**photovoltaic thermal plants**, **photovoltaic systems with heat pumps**, **geothermal storage with heat pumps**, and **biomethane production**—installed in livestock farms. Each system has distinct benefits and challenges that impact its viability in agricultural settings.

3.1 Photovoltaic Thermal Plants (PVT)

Photovoltaic thermal plants (PVT) combine the generation of electricity and heat in a single system, making them a potentially efficient energy solution for livestock farms that require both power and thermal energy.

Strengths

- **Dual-energy production**: Simultaneously generates electricity and heat, increasing overall efficiency.
- **Reduction in farm energy costs**: Offsets both electricity and heating needs, reducing reliance on external energy sources.
- **Compact footprint**: One system that produces both forms of energy can reduce land use compared to installing separate systems.
- **Opportunity of roof installation**: Livestock farms are generally made of buildings with large roof areas, without higher buildings or structures nearby; this represents an optimal location for PVT panels, also thanks to the eaves' slope, in particular on eaves facing South.

Weaknesses

- **High initial costs**: Installation and integration costs are generally higher than standard photovoltaic systems.
- **Complexity of installation and maintenance**: Combined systems require specialized knowledge for proper maintenance and efficient operation.
- **Limited heat application**: The generated heat may not always meet the specific heating requirements of livestock farms, depending on seasonal demand.

Opportunities

- **Growing demand for sustainable farms**: Consumers and markets increasingly value energy-efficient and sustainable farming practices.
- **Incentives for renewable energy**: Governments often offer subsidies or tax credits for systems that combine energy production methods.
- **Possibility of thermal storage**: farms are suitable for the implementation of long-term or short-term thermal storage, for the exploitation of heat from solar sources.

Threats

- **Weather dependency**: Performance can be compromised in regions with limited sunlight, reducing heat and power generation during critical periods.
- **Performance reduction in time**: the dust covering the PVT surface can reduce their performance, so periodical maintenance and cleaning are required.

3.2 Photovoltaic Systems with Heat Pumps

Photovoltaic systems combined with heat pumps can efficiently provide electricity for heating or cooling by capturing solar energy to run heat pumps that manage farm temperatures.

Strengths

- **Synergy between systems**: The electricity generated by photovoltaic panels can power the heat pumps, creating a self-sustaining energy cycle.
- **Reduced operating costs**: Farms can achieve substantial cost savings on energy bills by integrating this renewable solution.
- **Scalability**: The system can be scaled to fit the size and energy needs of any farm, from small to large operations.

Weaknesses

- **High upfront investment**: The combination of installing photovoltaic panels and heat pumps requires significant capital.
- **Efficiency dependent on climate**: The performance of both photovoltaic panels and heat pumps varies with sunlight and external temperatures, impacting overall efficiency.

Opportunities

- **Increased energy autonomy**: Livestock farms can become more independent from the grid, especially with efficient energy storage systems.
- **Technological advancements**: Improvements in solar panel efficiency and heat pump technology could further reduce costs and increase energy output.

Threats

- **Energy storage challenges**: Without sufficient battery storage, surplus energy generated during sunny periods may go to waste.
- **Seasonal energy demands**: Farms with high seasonal fluctuations in heating and cooling requirements might find the system less reliable in periods of low solar irradiance.

3.3 Geothermal Storage with Heat Pumps

Geothermal storage systems utilize underground heat storage, coupled with heat pumps, to provide efficient year-round heating and cooling in livestock farms.

Strengths

- **Stable energy source**: Geothermal systems provide a constant supply of heat energy regardless of external weather conditions.
- **High efficiency**: Heat pumps in combination with geothermal storage can significantly reduce the energy needed for heating and cooling operations on farms.
- **Long-term cost savings**: Although expensive to install, geothermal systems offer substantial savings on energy costs over time.

Weaknesses

- **High installation costs**: Drilling and installing geothermal systems, along with heat pumps, require a significant initial investment.
- **Complex maintenance**: System maintenance is more specialized and can be costly compared to other renewable energy solutions.
- **Restrictions related to environmental protection**: Environmental regulations in some regions may limit the temperature of heat injection underground.

Opportunities

- **Government incentives**: Some regions offer financial incentives for adopting geothermal energy, offsetting the high initial cost.
- **Energy security**: Geothermal energy provides a reliable, long-term energy source, reducing the need for fossil fuels on farms.
- **Space availability**: Geothermal systems need significant land area for installation, which is generally available in farmyards.

Threats

- **Land use limitations**: Farms in densely populated or geographically constrained areas may struggle to implement geothermal storage due to space or environmental regulations.
- **Technological obsolescence**: Advances in other renewable energy technologies (e.g., advanced solar or wind) could challenge the dominance of geothermal systems.

3.4 Biomethane Production

Biomethane systems in livestock farms capture methane from organic waste (e.g., manure) and convert it into biogas for energy, reducing both emissions and energy costs.

Strengths

- **Waste-to-energy conversion**: Livestock manure is transformed into a useful energy source, reducing farm waste and methane emissions.
- **Circular economy**: Biomethane systems create a sustainable cycle by using farm-generated waste to meet the farm’s energy needs.

- **Potential revenue stream**: Excess biogas can be sold to the grid or used to power additional farm operations.

Weaknesses

- **High setup and maintenance costs**: The construction and operation of biogas digesters require specialized infrastructure and expertise.
- **Efficiency depends on waste availability**: Biomethane production is directly tied to the volume of waste produced by livestock, which can fluctuate seasonally.
- **Limited scalability**: Smaller farms may not generate enough organic waste to justify the costs of installing a biomethane system.

Opportunities

- **Environmental regulations**: Stricter rules on methane emissions from agriculture increase the value of biogas as a compliance measure.
- **Growing demand for renewable fuels**: Biogas production aligns with the increasing demand for green energy solutions in agriculture and beyond.

Threats

- **Competition from other renewable technologies**: Solar, wind, and other renewable energy systems might prove more cost-effective for some farms.
- **Regulatory changes**: Shifts in environmental policy could affect subsidies or the economic viability of biomethane production.

4 CONCLUSIONS

The project RES4LIVE developed several specific best practices for the defossilization of livestock farms, namely:

- Best practices of solar plants
- Best practices of PVT systems for swine farms
- Best practices of PVT systems for cattle farms
- Best practices of PVT systems installation
- Best practices of PV systems for poultry farms
- Best practices of heat pumps
- Best practices for heat pump installation
- Best practices for using multi-source heat pumps in heating swine farms and controlling the environment in poultry houses
- Best practices of geothermal storage (BTES)
- Best practices of biomethane plant
- Best practice of on-farm production and upgrading of biogas to biomethane and BioCNG fuel
- Best practices of adaptation of a farm tractor for biomethane use
- Best practice of smart control with sensors
- Best practice of ventilation of livestock building
- Best practices for heat pump control

Each renewable energy system analyzed presents peculiar strengths and weaknesses in the context of livestock farms. Photovoltaic thermal plants and photovoltaic systems with heat pumps offer scalable, efficient solutions with the added benefit of renewable electricity generation, while geothermal storage and biomethane production provide long-term sustainability with energy independence. However, high initial costs and operational complexities present challenges across all systems. The choice of technology will largely depend on farm size, location, energy needs, and access to financial incentives, all while considering the broader impact on environmental sustainability and operational efficiency.

The research and the installations carried out led to the definition of technical parameters useful for the design and implementation of the above best practices. Moreover, the performances of the RES systems installed were measured and assessed, thus providing a quantitative indication of the most suitable solutions which can be considered for various application contexts, with a focus on livestock farms.