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Scenario-Based Comparison of Sustainable Heating and Cooling Systems for Piglet Production Systems

Konstantin König[1], Felix Pag[1], and Klaus Vajen[1]

[1] Department of Solar and Systems Engineering, University Kassel, Germany

*Correspondence: Konstantin König, solar@uni-kassel.de

Abstract. Industrial pig farming is a highly energy-intensive activity due to the susceptibility of extensively bred pig breeds. To ensure efficient production, optimal climatic housing conditions are necessary. In this context, reducing CO2 emissions requires maximizing efficiency in heating and cooling provision, including a significant renewable energy component. However, pig farmers face a perpetual demand to refine their production methodologies due to evolving regulatory standards and market demands. This demand influences the efficacy of existing heating and cooling strategies. To address these challenges, a comprehensive case study was undertaken at a sizable piglet farm to devise a methodology that facilitates the projection of annual heating and cooling load profiles. This methodological framework is suitable for use in similar agricultural settings with comparable operational constraints. The proactive projection of heating and cooling load profiles constitutes a foundational step in evaluating potential heating and cooling systems with regard to their energy utilization, financial viability, and carbon footprint. Central to this evaluation are the comparative analyses of heating systems such as biogas and heat pumps, alongside cooling systems exemplified by compression chillers and absorption chillers.

Keywords: Heating Demand, Cooling Demand, Pig Farming, Pig Housing, Piglet Production Systems

1. Introduction

In the contemporary agricultural landscape, the continual adaptation and advancement of piglet production systems are imperative, driven by evolving market demands and changing regulatory requirements. Sustaining market competitiveness mandates a responsive approach from pig farmers to the volatile market dynamics, potentially necessitating structural alterations to pig housing infrastructure, thereby influencing the capacity for animal occupancy and consequently augmenting the demand for heating. Augmenting the housing environment through cooling interventions during warmer seasons holds promise for enhancing both production efficacy and animal welfare. The structural modifications to pig housing and the optimization of housing conditions exert a discernible influence on heating requirements, thereby underscoring the imperative for enhanced cooling efficiency. Furthermore, the imminent phasing out of subsidies for a substantial portion of Germany's 9,600 biogas plants bears significant ramifications for pig farmers, prompting a reassessment and scrutiny of extant heat supply systems [1]. Against this backdrop, the comparative analysis is directed towards scrutinizing the efficiency of heating systems, namely biogas and heat pumps, alongside cooling systems typified by compression and absorption chillers. A pivotal preliminary step in facilitating this comparison involves the prognostication of heating and cooling load profiles for piglet farms. To this end, a methodological framework is devised to prognosticate prospective heating and cooling load profiles across varied scenarios, leveraging extant heat demand data and climatic metrics recorded within piglet production systems. The predictive modeling of heating and cooling load profiles furnishes an indispensable foundation for juxtaposing prospective heating and cooling systems in terms of energy consumption, economic viability, and carbon emissions. Within the spectrum of pig production, a fundamental distinction can be drawn between piglet production and pig fattening stages. Notably, within the piglet production paradigm, heating requirements account for a substantial majority, constituting 87% of the total energy demand, while in pig fattening, this figure stands at 66% [2]. The methodological focus and subsequent comparative analyses are exclusively centered on intensive pig production systems, with a particular emphasis on piglet production, while pig fattening processes are deliberately omitted from consideration.

2. Pig production system and requirements of indoor environment in pig housing systems

The gestation period of a sow spans from 112 to 115 days. After weaning, piglets remain under the care of the sow for a duration of 21 to 28 days, during which they are nursed. Subsequently, they are transferred to dedicated piglet housing for a period of around five weeks. Upon reaching a weight of 30 kg, the piglets are then moved from the piglet housing to fattening quarters. The provision of optimal environmental conditions plays a crucial role in ensuring the optimal performance of the animals at various stages of development. Table 1 outlines the recommended temperature ranges conducive to achieving performance targets. The piglet production and rearing phase, lasting approximately 170 days, is characterized by temperatures reaching up to 32 °C. Consequently, this phase emerges as a significant driver of heat demand within the pig production continuum [3]. The necessity to maintain these optimal air temperatures underscores the imperative for both heating and cooling provisions within the housing facilities.

The heating is currently provided by underfloor heating or wall radiators and heat lamps in piglet nests. If the housing has a cooling system, high-pressure evaporative cooling is the main method used. Additionally, ventilation systems are used during summer months to maximize the air volume flow and protect the pigs from heat stress. During the winter months, there may be a decrease in air flow, but it remains crucial to remove harmful gases. Nevertheless, this exchange of air results in significant loss of heat.

3. Case Study

The case study is located in Thüringen, Germany and involves a facility housing 5,000 sows and 160,000 piglets. The case study incurs an annual heat demand of 5 gigawatt-hours (GWh) and an annual electricity demand of 2.6 GWh. From the measured heat flow and housing climate data of the studied piglet production unit, heating and cooling load profiles are generated. These profiles will serve as the basis for evaluating and comparing the heating and cooling systems. Figure 1 displays the heating, cooling, and electricity demand of the investigated piglet farm, alongside the electricity and heat generation of the CHP unit.

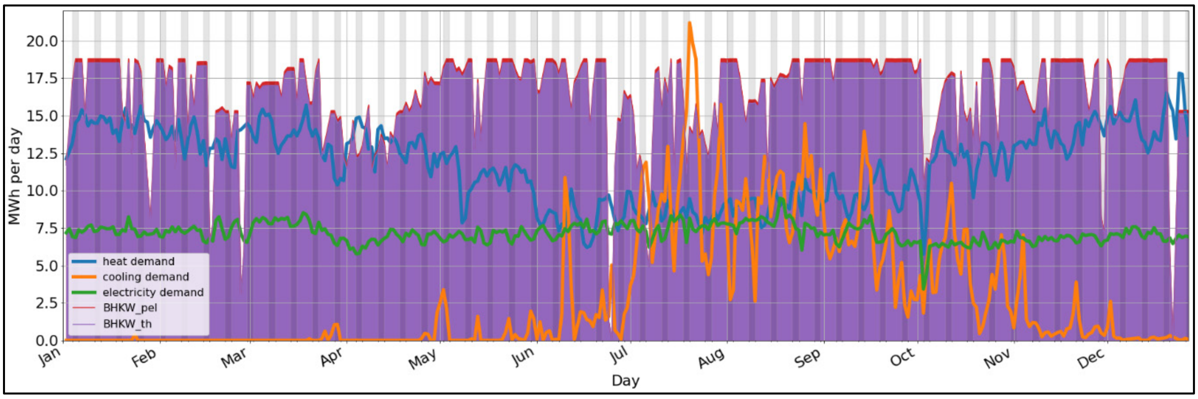

Figure 1. *Comparison of annual heating, cooling, and electricity demand of investigated piglet farm with daily electricity and heat production of CHP unit in 2021*

4. Head demand scenario

In the context of highly industrialised factory farming, the case study under consideration was limited to data solely pertaining to annual electricity consumption, with no corresponding information regarding heat consumption. To address this limitation, specialised heat meters had to be installed, which was associated with considerable expenditure and logistical effort. Due to regulatory constraints in the sector, mobile heat flow meters could not be used inside the stables to prevent potential contamination from human pathogens to the livestock. Therefore, these meters were only placed outside the stable premises, usually at the heating distribution point, which prevented the measurement of heat demand within individual compartments. In contrast, information regarding electricity consumption or load profile can be easily obtained from the energy supplier, making it a more accessible source of information. Therefore, the first step in the investigation was to use the electricity load profile to gain initial insights. Particular emphasis was placed on the ventilation system, as it significantly influences the ambient conditions within the housing environment, depending on factors such as stable temperature and external climatic conditions. This approach facilitated the initial derivation of conclusions regarding the diurnal, weekly, and seasonal patterns of heat demand, based on the analysis of the electricity load profile.

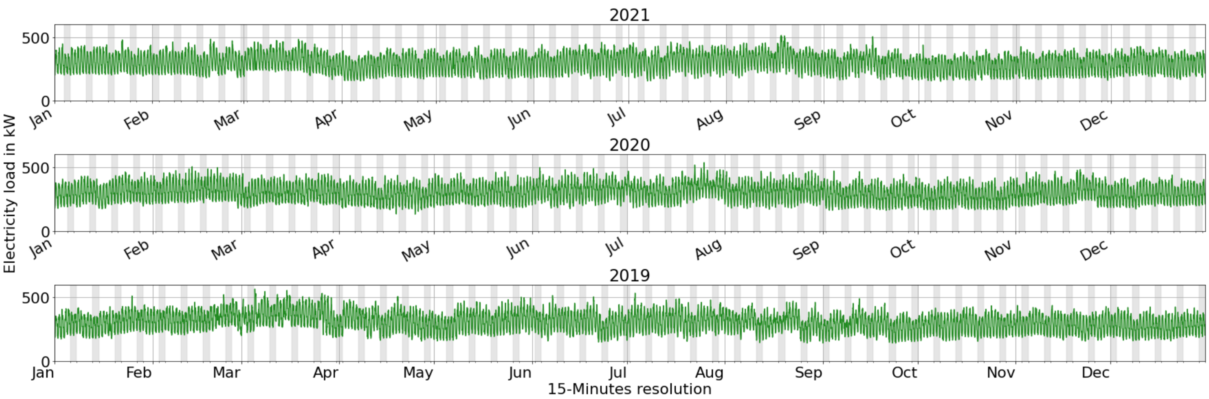

Figure 2. *Hourly resolution of the annual electricity load profile for the examined piglet facility throughout the years 2021, 2020 and 2019.*

Figure 2 shows the electricity load profile for the years 2021, 2020 and 2019. The analysis indicates that there were no significant deviations across the years, suggesting consistent production levels and adherence to a regular farrowing cycle. This stability is also presumed to apply to the determination of heat demand within the operation. The examination of the electricity load profile reveals a relatively uniform distribution of electricity consumption over time, without any pronounced seasonal variations.

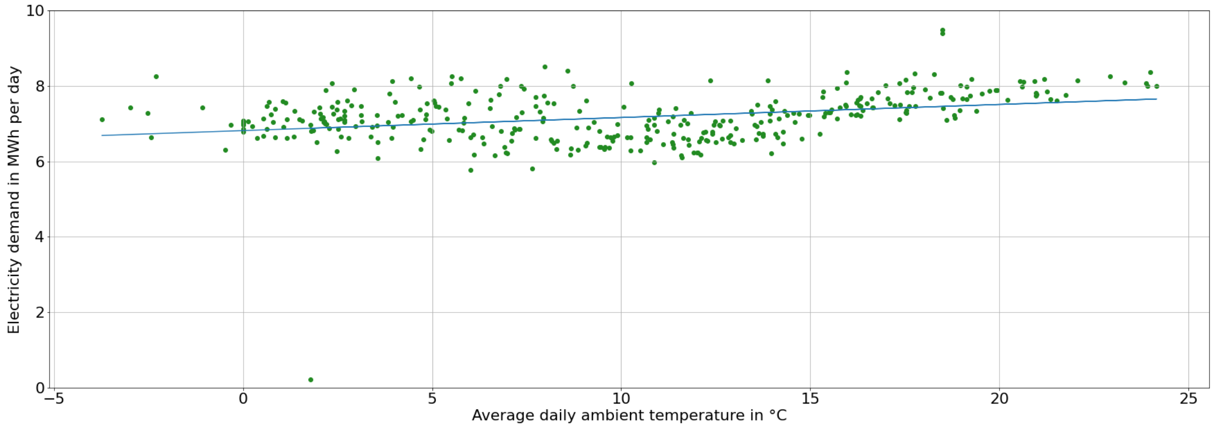

Figure 3. *Correlation between electricity demand and the average ambient temperature within the examined piglet facility.*

In contrast to Figure 2, Figure 3 shows a slight correlation between electricity consumption and ambient temperature. This correlation is due to the increase in stable temperatures resulting from the elevation of ambient temperatures. To maintain the welfare of the pigs and ensure optimal air temperatures, the ventilation system's air exchange rates are increased accordingly. The correlation between electricity load and heat demand is supported by the deliberate reduction of air exchange rates by farmers during winter months to mitigate heat loss. This establishes a relationship between the two variables, as both are influenced by the climatic regulations governing the stable environment. Figure 4 provides evidence of the similar dependence of heat demand on ambient temperature.

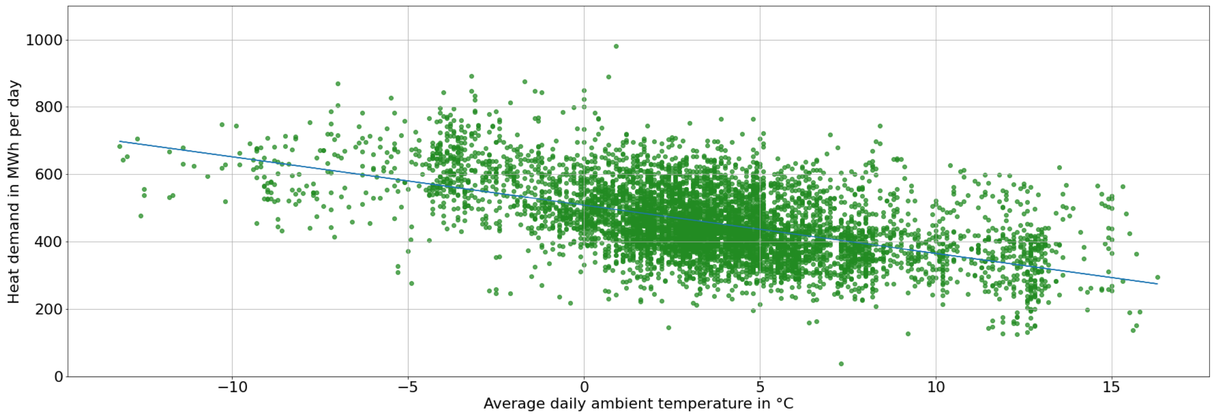

Figure 4. *Correlation between heat demand and the average ambient temperature within the examined piglet facility, displayed at hourly resolution.*

The findings indicate a discernible dependence of the heat load profile on ambient temperature, which is consistent with the observations made by [4]. The heat demand load profile for the examined piglet farm is computed for the entirety of the year based on a shorter-term heat flow measurement. The heat load profile is depicted in Figure 5.

Figure 5. *Hourly resolution of the annual heat load profile for the examined piglet facility throughout the year 2021/22.*

5. Cooling demand scenario

Figure 6 illustrates the temperature differentials between the set temperature and the actual stable temperature within the examined piglet facility throughout the year. A consistent deviation is observed across all seasons, suggesting potential issues with temperature control mechanisms. Interestingly, despite an escalated air exchange rate during summer months, the deviation intensifies, indicating a propensity for temperature overshoot. This phenomenon underscores the necessity for implementing cooling systems, as observed in some farming operations, and emphasizes the imperative of factoring in cooling demand when devising an energy-efficient infrastructure.

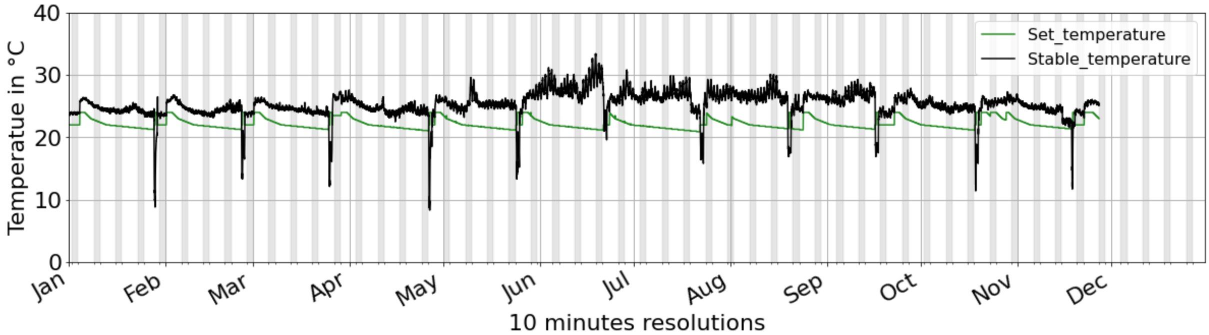

Figure 6. *Illustration depicting the set temperature and stable temperature within one farrowing stable of the examined piglet facility, presented at a 10-minute resolution.*

In addition to ambient temperature considerations, the sensitive heat generation of animals must be factored into the calculation of cooling demand within a stable environment. Key determinants of sensitive heat production include the animal population density within each compartment, their individual weights, and their daily weight gain. Accounting for these variables, sensitive heat production can be quantified using eq.1 as outlined in the DIN 18910 [5]. Within the context of the case study, particular attention is directed towards the farrowing pen and the gilts pen concerning cooling requirements. This focus is driven by the imperative to prevent overheating of farrowing sows and to optimize production and growth rates of gilts.

Sensitive heat production:

$$q_{sen} = 0.62 * q_{tot,cor} - \frac{q_{tot}}{1000} * (1.15 * 10^{-7} * T_i^6) \tag{1}$$

Figure 7 portrays the cooling demand profile of the investigated piglet farm, demonstrating a pronounced peak during the summer period. In typical intensive pig production setups, such as the subject of this case study, a biogas plant integrated with a Combined Heat and Power (CHP) unit is commonly employed. Interestingly, in this particular case study, the timing of the cooling demand coincides with the excess heat output from the CHP unit, as depicted in Figure 7. This alignment presents an opportunity to leverage the excess heat for cooling purposes, particularly through the implementation of absorption cooling methods to reduce the temperature of supplied air and regulate stable temperatures to optimal levels. This strategy offers the advantage of enhancing housing conditions without significant additional energy expenditure, as the surplus heat is currently dissipated during the summer months.

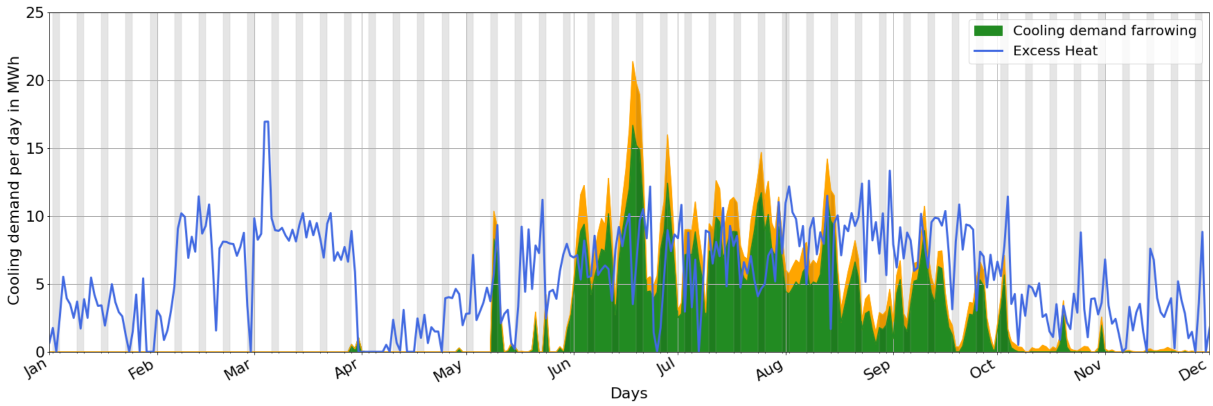

Figure 7. *Cooling demand for the stables and excess heat from the combined heat and power (CHP) system at the analyzed piglet farm.*

6. Methodology

Figure 1 demonstrates the simultaneous occurrence of heating and cooling demands, necessitating concurrent generation strategies. In this context, an integrated heat pump emerges as a potential alternative to a Combined Heat and Power (CHP) system coupled with a chiller. The integrated heat pump offers enhanced efficiency when both heating and cooling generation functions are employed. Consequently, this study undertakes a comparative assessment of heating and cooling systems, considering the presence or absence of subsidies, to ascertain the viability of substituting the biogas plant with an integrated heat pump. Furthermore, the study evaluates the impact of cooling systems on energy consumption, costs, and CO2 emissions, and identifies the most suitable cooling system for integration with the biogas plant. The heating and cooling systems under investigation encompass a combination of diverse technologies falling within the following categories:

- Category heat production: Biogas CHP, Heat pump
- Category subsidies for electricity feed-in: subsides, no subsides
- Category heat storage: Heat storage 0 m^3 and 100 m^3
- Category cooling: Compression chiller, absorption chiller

Figure 8 depicts the comprehensive array of energy systems subject to evaluation and comparison. In order to appraise potential heating and cooling systems across metrics of energy utilization, economic viability, and CO2 emissions, pivotal indicators were identified. These indicators furnish insights into the holistic environmental and economic ramifications. Energy usage is scrutinized through assessment of secondary energy demand, while economic efficiency is gauged by juxtaposing the Levelized Cost of Electricity (LCOE) and Levelized Cost of Heat (LCOH), alongside overall energy expenses. Facilitating emission comparisons, the CO2 factor is computed per kilowatt hour (kWh) of generated power.

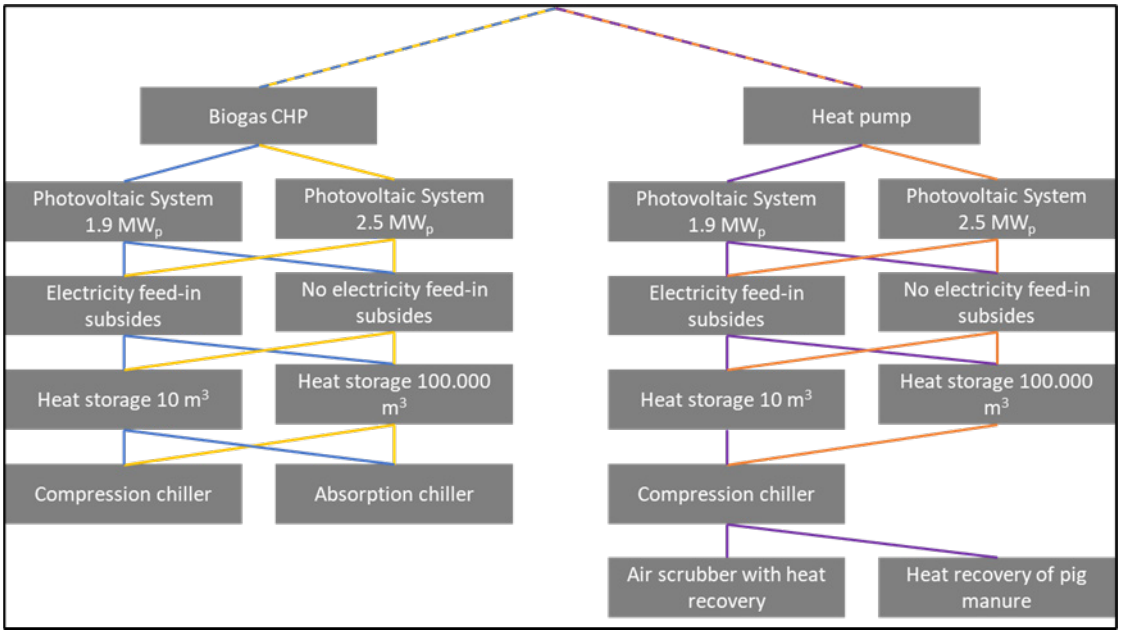

Figure 8. *Energy systems that undergo evaluation and comparison*

7. Results

Figure 9 presents the secondary energy demand of the analyzed energy systems. It is apparent that energy systems incorporating compression cooling demonstrate elevated electricity consumption, but reduced biogas utilization compared to those employing absorption cooling. Remarkably, the heat pump exhibits the lowest overall secondary energy demand among all energy systems, albeit nearly doubling the electricity consumption while entirely eliminating the need for biogas. For the remaining systems, achieving a balance between electricity consumption and biogas usage proves crucial, as none of the remaining energy systems succeed in simultaneously reducing both types of consumption.

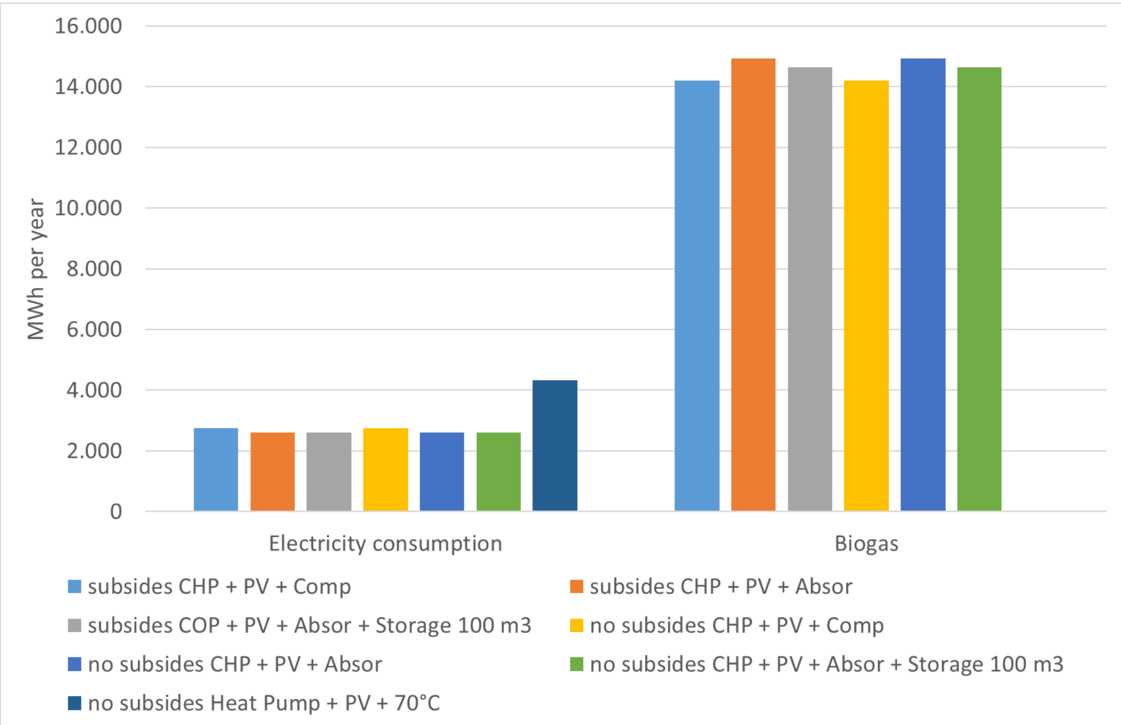

Figure 9. *Secondary energy demand of energy systems*

The heat pump exhibits the lowest CO2 emissions, as evidenced by Figure 10, attributable to its minimal secondary energy demand. Furthermore, energy systems receiving no subsidies demonstrate a notable reduction in CO2 emissions, primarily stemming from the direct utilization of electricity generated by CHP and the photovoltaic (PV) system. This results in a significant decrease in electricity consumption and, consequently, in CO2 emissions, which are then solely attributed to biogas usage. However, the emissions associated with biogas remain unchanged between subsidized and non-subsidized scenarios, as CHP units maintain consistent electricity-driven operation, thereby ensuring a steady electricity output. Notably, energy systems incorporating compression refrigeration systems exhibit lower CO2 emissions compared to those utilizing absorption refrigeration technologies, because of the higher demand on biogas.

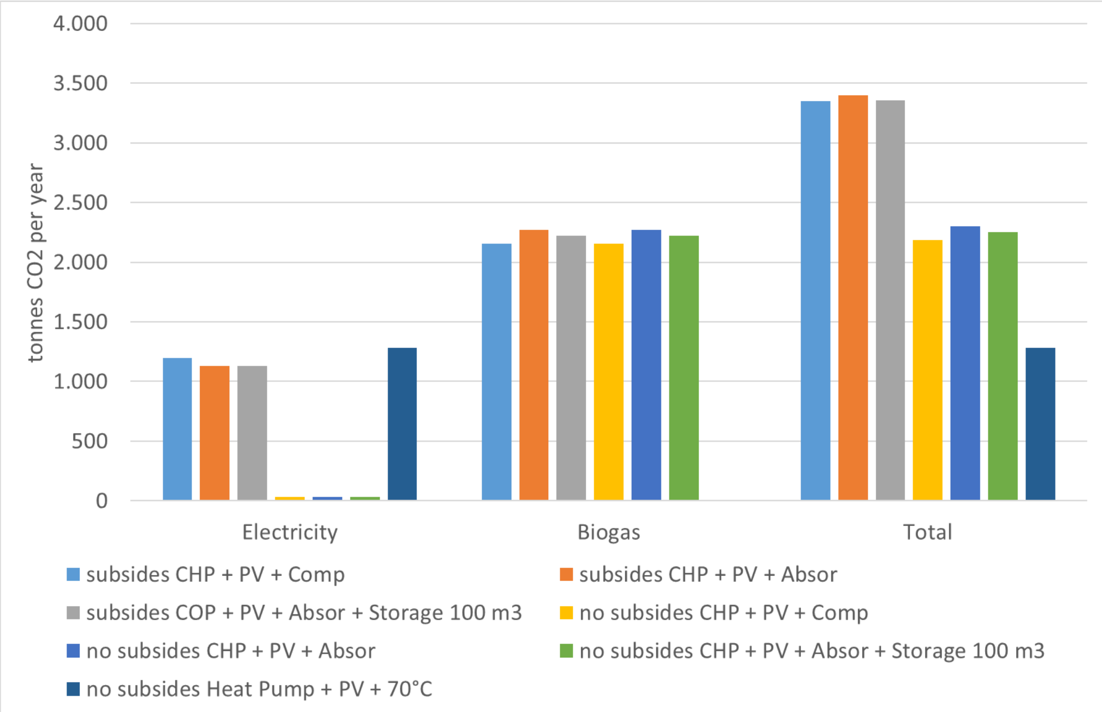

Figure 10. *CO2 emission of energy systems*

The depictions of LCOH and LCOE in Figure 11 present an intriguing scenario, wherein the electricity generation from the CHP and the PV system yields negative LCOE. Furthermore, it is evident that the heat pump, despite excelling in terms of CO2 emissions and secondary energy demand, exhibits both the highest LCOH and LCOE, rendering it less economically favourable. In contrast, energy systems employing compression chillers demonstrate higher LCOH and reduced LCOE savings compared to systems employing absorption cooling. The elevated LCOH observed in energy systems with compression chillers can be attributed to consistent electricity-driven operation of the CHP unit, thereby generating greater excess heat than absorption cooling systems, which capitalize on this surplus heat. Conversely, the savings in LCOE are diminished with compression refrigeration systems due to heightened electricity consumption, resulting in reduced electricity fed into the grid and subsequently lower revenues from feed-in tariffs.

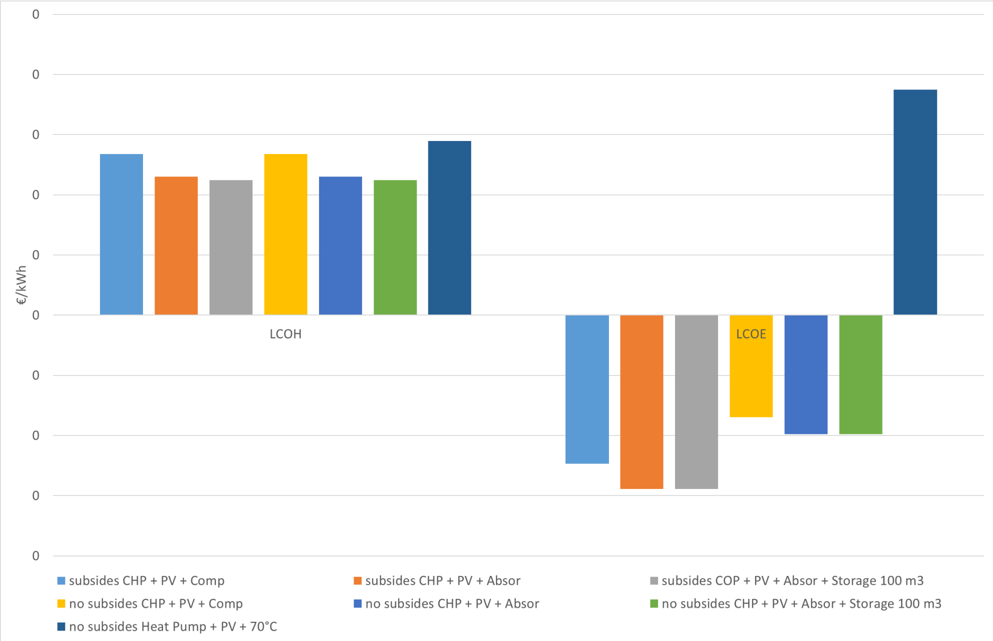

Figure 11. *LCOH and LCOE of energy systems*

8. Outlook

Considering multiple options for heating and cooling provision offers the advantage of anticipating future changes based on diverse load profiles, facilitating the selection of the most energy-efficient and cost-effective concept for the analyzed farm. Detailed planning must take into account the specific conditions of the site of operation. The comprehensive methodology outlined in this paper encompasses the creation of heating and cooling load profiles and the evaluation of heating and cooling systems for a piglet farm, with a focus on energy consumption, economic efficiency, and CO2 emissions. When evaluating the three parameters - energy consumption, economic efficiency and CO2 emissions - for the energy systems compared, no clear result can be expected, as this case study shows. While the heat pump achieves the best results in terms of overall energy consumption and CO2 emissions, it proves to be the least economical option compared to the combination of a CHP system with a compression refrigeration system or an absorption refrigeration system. For this case study and the evaluated energy systems, the economic and ecological objectives are at odds, necessitating a careful consideration of which goal holds greater significance on an individual basis.

Data availability statement

The data is not accessible to the public as it is proprietary business information.

Competing interests

The authors declare that they have no competing interests.

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