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# Economical and ecological optimization of renewable energy solutions for thermal demands of livestock barns

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## Abstract:

This work targets sustainable livestock farming, with the aid of cost-effective, novel renewable energy sources (RESs). A literature review showed that evaluating the energy consumption in the livestock sector is not straightforward. Therefore, a model was made to estimate the heating and cooling demands of a pig farm throughout the year. Various combinations of RES technologies are compared with respect to the current installation and an economic and ecological assessment is performed. The possible technologies are: PV panels, PVT panels, solar collectors, heat pumps, wind energy and batteries (both thermal and electrical). The assessment allows estimating the investment cost, life-cycle cost (LCC) and greenhouse gas (GHG) emissions from energy usage of different selections and sizes of renewable technologies. The boundary conditions for the studies are taken from an actual pig farm in Belgium. Autonomous energy creation with solar energy and/or wind generation in combination with a heat pump proves to be the most promising solution to reduce GHG emissions according to the model. The model and results will be evaluated with actual performance data by means of installing heat pumps, PVT panels and thermal storage at the pig farm.

## Keywords:

Renewable energy, livestock, pig farm, energy optimization, economical assessment, prediction model

## 1. Introduction

According to Paris et al. [1], the livestock sector is one of the main energy consumers in the European Union (EU). A large part of this energy is still provided by fuel oils and natural gas. The goal of RES4LIVE[1], a project that received funding from the European Union's Horizon 2020 research and innovation program (grant agreement No 101000785), is to defossilize the livestock industry by researching the implementation of optimized designs and combinations of RES. Looking at the energy needs of different farms, an optimal solution based on investment cost, life-cycle cost (LCC) and greenhouse gas (GHG) emissions should be calculated. In the current work, the model developed for this purpose is explained and some initial results are presented.

The goal of Section 2. is to frame the energy consumption of livestock in the EU and Flanders (a region in Belgium). In 2021, a survey was held in Flanders about energy consumption in pig farming whose results can be found at the end of the section. In Section 3., the calculation model (made in Python) is explained as well as its application to a pig farm in Belgium called the 'Varkenscampus', together with the corresponding sensitivity analysis. At the end, some remarks about future work are presented.

## 2. Energy consumption in livestock

Even though the livestock sector is claimed to be one of the main energy consumers in the EU by Paris et al. [1], there is no standardized methodology to measure the energy usage in livestock. At the moment, the livestock's energy consumption pattern is derived from literature reviews or by performing analyses in a local environment. There is no detailed database available yet. In this section, the currently known energy usage in the livestock sector is discussed on three different levels. First, a literature review is performed to frame the energy consumption in livestock across the EU. Secondly, a biennial study performed by the Department of Agriculture and Fisheries about agriculture in Flanders (Belgium) is discussed. Thirdly, a recent survey was launched whose results are reported in this work.

### 2.1. Energy consumption in livestock across the EU

In Paris et al. [1], a literature review was conducted by the Agricultural University of Athens that gathered some papers on the subject. The review summarizes several direct and indirect energy uses from several livestock

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[1] res4live.eu/

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farms including dairy cattle, beef cattle, pigs, laying hens and broilers. Direct energy covers all energy used on the farm, while indirect energy refers to all outside usage, e.g. feed processing. To be able to equally compare energy consumption across all types of livestock farms, it is scaled per amount of end product produced by the farm. For all livestock categories, this is done per kg produced meat or eggs, except for milk production. To obtain similar values for milk, a unit is needed that takes into account the extra fat and protein production. The energy corrected milk production (ECM), expressed in kg, is the unit that fulfills this purpose. The total energy consumption can be roughly estimated by taking the mean of the results reported by Paris et al. [1] and multiplying these with the total production in Europe. This is done to obtain the total energy usage mentioned in Table 1.

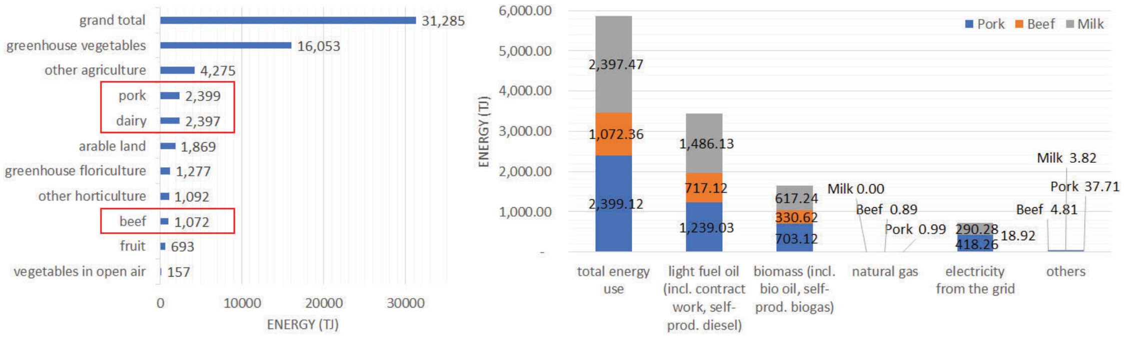
**Table 1**: Estimation of the total energy consumption of different livestock farms across Europe in one year according to Paris et al. [1], the † indicates a number that could not be retrieved from Paris et al. [1] and was extracted from the Eurostat database [2] instead, with the mean weight of an egg assumed to be 60g.

| Livestock type | Total production in the EU [$10^9$ kg] | Avg. energy per kg production [MJ/kg] | Total energy usage in the EU [$10^{10}$ MJ] | Direct energy [%] |
|---|---|---|---|---|
| Dairy cattle | 158 | 3.7 | 58 | 15-48 |
| Beef cattle | 7.9 | 49.9 | 39 | 60-70 |
| Pork | 23.8 | 19.3 | 46 | 20 |
| Poultry meat | 15.29 | 14.36 | 22 | 25 |
| Laying hens | 4.35 † | 22 | 9.6 | 25-46 |

From the results reported by Paris et al. [1], it can also be concluded that the main contributor to energy consumption is the feed (indirect). In this paper however, the focus lies on the direct energy consumption. The percentage of direct energy consumption is indicated in Table 1. Although it is not as large as the contribution of the feed, it is still significant, especially in laying hens and beef production. A large share of this on-farm energy consumption is still produced by fossil fuels. Other energy sources are the electricity grid (still lacking green sources in many countries) and natural gas. By converting this direct energy consumption to renewable energy sources (RESs), a noteworthy improvement can be made in the climate impact of livestock.

## 2.2. Energy consumption in livestock across Flanders (Belgium)

In Flanders, the Department of Agriculture and Fisheries publishes an exhaustive report every two years about all agricultural related activities. Their most recent report [3] was written in 2017, but biannual updates can be consulted at [4]. In Fig. 1, a brief summary of the results concerning energy consumption in livestock is given. Pork, dairy and beef take up about 20% of the total energy consumption in Flanders. Poultry has been left out of this discussion due to insufficient data available.



(a) (b)

**Figure 1**: Results adapted from the Department of Agriculture and Fisheries [4] about (a) the energy consumption of agriculture in Flanders per sector with livestock indicated by red rectangles and (b) the energy consumption in livestock per carrier, poultry is not mentioned in this data since there is no detailed data available yet.

As can be seen in Fig. 1b, most energy comes from light fuel oils, such as gasoline and diesel fuel. The main consumers of these fuel oils are tractors for tillage. Another purpose is additional heating during winter by

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e.g. heat canons. The latter is mostly for pigs, since cows do not need as much heat. Runner up is biomass, which shows that Flemish farmers have been making efforts in using cleaner energy. The energy balance [4] reported by the Department of Agriculture and Fisheries over the past 10 years, shows a rise of about 10 000 TJ in biomass energy generation across all agriculture. The biggest consumer of natural gas in Flanders is the pig industry. This phenomena can be attributed to the use of hot water systems for floor heating, providing the high heating needs for piglets, and sanitary hot water, used for cleaning and showers. According to Paris et al. [1], electricity from the grid is mainly used for ventilation, present in all livestock farms; heat lamps, appearing mostly in pig farms; and milk cooling for dairy cattle. Beef cattle requires the least amount of electricity. The Department of Agriculture and Fisheries [4] shows that during the last 10 years, the latter sector even produced a net amount of electricity by installing photovoltaic (PV) panels on their large roofs. Other energy sources are thus mainly solar panels, but can also be small wind turbines, heat pumps etc.

## 2.3. Energy survey in pig farming across Flanders

In 2021, a survey was launched by Flanders Research Institute for Agriculture, Fisheries and Food (ILVO) for Flemish pig farmers. This survey was meant to probe their current energy installations. There were 38 correspondents composed of 25 farrow-to-finish (farmers that have a sow herd to breed piglets and rear these from birth to slaughter - so the entire life-cycle of the pig), 11 fattening pig farmers (farmers that buy piglets and rear them until slaughter) and 2 sow farmers (farmers that have a sow herd to breed piglets and sell these piglets). In this subsection, the results are presented. Initially, the heating system of the participants' farms was asked. Heating is the main energy consumer in pig farming, since newborn piglets need a high temperature of about 35°C. In intensive pig farms, it is not unusual to have new piglets every three weeks meaning this high temperature demand is often required. Therefore, knowing the heating system offers valuable information about the energy consumption of the farm. The results about current installations can be found in Fig. 2. Most of the pig farmers still use fuel oil to heat up their farms. This result is in line with the literature review performed by Paris et al. [1]. It indicates that improvement is still possible in many farms. Almost all participants already took measures to reduce their energy consumption, especially on electricity.

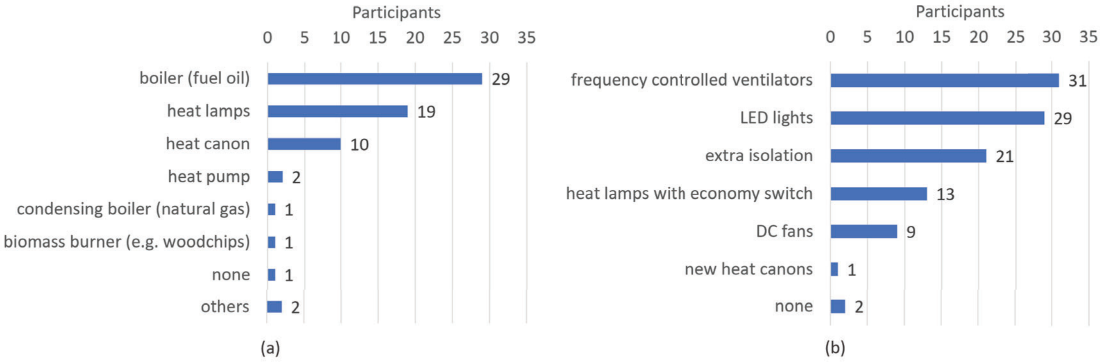

**Figure 2**: Survey results about energy consumption in pig farming with the horizontal axes representing the amount of participants (38 in total): (a) presents the currently installed heating systems on the participants farms and (b) which measures they already took to reduce their energy consumption.

In the next part of the survey, the participant's motivation about switching to renewable energy sources was questioned. All participants were asked to rate the importance of a project on introducing renewable energy in pig farming on a 5-point scale. The results of the survey were that 76.3% of participating pig farmers scores this type of project with an importance of 4 or 5 out of 5. Of the respondents, 92.1% thinks more energy saving measures are possible on their farm and 76.3% already owns a renewable energy source. These numbers conclude that switching to renewable energy is deemed important among pig farmers. Most of the farmers already made some efforts, but still think more energy saving measures are possible on their farms. This can also be concluded from the results in Fig. 3, in which their encountered difficulties were questioned. Lack of investment budget and insufficient knowledge about the needed capacity, system requirements and current legislation are the main obstacles for farmers.

From this section, it can be concluded that livestock in general has a high energy demand and a lot of improvement can still be made to convert to clean energy. In the residential and industrial sector, many optimized and adapted RESs are already present. The goal of this work is to evaluate these solutions for the livestock sector. A generally applicable calculation tool was created to optimize the combination and design of RESs

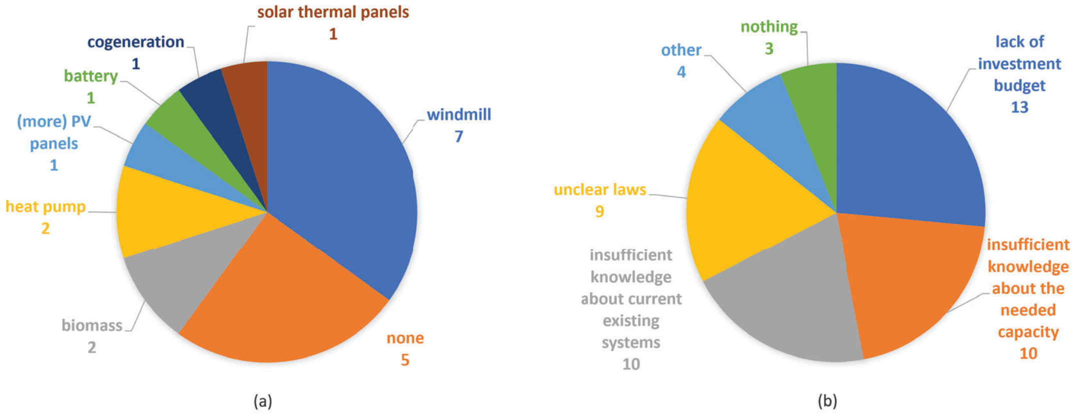

**Figure 3**: Survey results about energy consumption among pig farmers (38 participants): (a) which RESs the participants are considering and (b) the barriers they encounter to install (more) RESs.

for farm-specific cases. In the next part of this paper, the simulation methodology is explained and applied to a pig farm in Belgium, called the ‘Varkenscampus’. The calculated parameters are investment cost, LCC and GHG emissions. Such a tool could fill the gap of insufficient knowledge about system requirements and needed capacities of RESs by livestock holders.

# 3. Calculation tool

A calculation tool was made in Python to find optimal combinations of RESs that are fine-tuned to the specific energy demands of livestock farms. A first version was made by Faes [5]. This paper expands further upon this tool and tests its sensitivity to several parameters. The calculation is based on the Varkenscampus, located in Melle (Belgium). This is a commercial farrow-to-finish pig farm with a maximum capacity of 136 sows, 576 piglets, 640 fattening pigs, 12 young sows and 2 boars. This puts the Varkenscampus into the category of a small to medium pork producer. Currently, the energy demand of the farm is provided by a connection to the grid and a condensing natural gas boiler. The electricity is mainly used for ventilation and heat lamps, while the condensing boiler provides hot water for floor heating, air heating and sanitary hot water. The tool takes into account past energy consumption patterns and satisfies this demand with predefined combinations of RESs. Subsequently, the investment cost, LCC and GHG emissions can be calculated for every combination. Finally, the optimal combinations are found by using Pareto optimization.

## 3.1. Explanation of the tool

The Python tool consists of multiple parts, each of which is explained below. The starting point is the construction of an hourly energy demand of the farm. These energy requirements must always be met, otherwise there would be discomfort for the animals. A reference case is obtained by implementing parameters of the current (existing) condensing gas boiler. Finally, the calculated output parameters of all the possible installations are scaled to this reference case.

### 3.1.1. Estimation of the energy demand

An hourly energy demand is required as input for the tool. To achieve this, the energy demand is separated into two flows: the electricity demand and the heat demand.

**Electricity demand**

The electricity demand profile of the farm is constructed based on monthly measurements at the Varkenscampus. The monthly usage was averaged out to obtain an hourly mean value. The total electricity demand of the farm in the year 2020 was 107 MWh.

**Heat demand**

The calculation of the heat demand is less straightforward since it cannot be measured directly and many factors need to be taken into account. These factors, among other things, consist of:

- The farm’s building materials and isolation.
- The amount of pigs per compartment and their heat production.
- The complete heating system (sanitary hot water, air heating, floor heating etc.).
- The required heating and/or cooling for the pigs.
- Ventilation and relative humidity at which the pigs feel comfortable.

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- The weather conditions outside.

In 2021, the calculations were performed by De Win [6] and eventually adjusted by Faes [7]. They created a steady-state model, which calculates the heat flow in and out of the barn. Documentation of the barn's building process provided the necessary information on the building's properties. From a literature study [8], the heat production and comfort requirements of pigs can be found. Subsequently, the hourly heating/cooling demands for air and underfloor heating can be estimated. This is done per compartment to take into account the occupation rate, age of the pigs and existing heating system. For example, some compartments have no air heating installed, while other ones require both air and floor heating. Different compartments will also have different ages of pigs at any time, which effects the heat production and comfort needs in that compartment at that moment.

In the end, two separate hourly heat demands were obtained: one for the high temperature water cycle (60°C) used for air heating (twin tubes), and one for the low temperature water cycle (40°C) used for floor heating. The high temperature heat demand is calculated by taking the required heat demand of every zone. It takes into account all of the above-mentioned factors. The low temperature heat demand is calculated with the characteristics of the heating mats in combination with the weekly occupation rate of newborn piglets of the farm in 2020. When piglets are present and they are younger than 4 days, the 16 available heating mats (each able to deliver 180W) are put at full power. When the piglets have the age of 4 to 7 days, the mats are put at half their power. In 2020, new piglets were born every 21 days. Consequently, the low temperature heat demand follows a periodic cycle of 21 days with 3 separate values per zone depending on the age of the piglets. In the end, the calculated heat demand in 2020 is about 212 MWh corresponding to an estimated consumption of 20,000 $m^3$ natural gas.

### 3.1.2. Selection of RES

In a next step, the model adds a selected combination of RESs to the current installation. These combinations are shown in Table 2. The currently installed natural gas boiler is included in the first row and taken as the reference point. The selection is made by taking the size of the Varkenscampus into account. As can be seen, the heat pump options are chosen in pairs indicated by a pair of brackets. Considering the two different heat demand profiles, it is more efficient to have two separate heat pumps with one operating continuously than one of a bigger size operating in on/off mode [6]. Running over every possible combination results in 123,480 possible scenarios, however not every scenario is sensible. Batteries are useless without an autonomous source of electricity and are therefore left out of the calculation if no such source is present in the scenario.

**Table 2**: Selection of energy systems to be calculated by the model, the square brackets are used to indicate a pair of heat pumps in the configuration, with first the high temperature heat pump (60℃), and second the low temperature heat pump (40℃).

| Energy system | Unit | Options |
|---:|:---:|:---|
| natural gas boiler | kW | 60 |
| PV panels | $m^2$ | 0 – 10 – 50 – 100 – 500 – 1000 |
| ST panels | $m^2$ | 0 – 10 – 50 – 100 – 500 – 1000 |
| PVT panels | $m^2$ | 0 – 10 – 50 – 100 – 500 – 1000 |
| heat pump(s) | kW | 0 – [60, 0] – [55, 15] – [30, 30] |
| electrical battery | kWh | 0 – 2 – 5 – 10 – 100 |
| thermal storage (water) | liter | 0 – 250 – 800 – 1000 – 2500 – 3000 |
| wind turbines | kW | 0 – 15 – 30 |

For every scenario, a steady-state model for the energy flow over a period of one year is performed. Besides the electricity and heat demand of the barn (see 3.1.1.) and the sizing of possible RESs combinations (Table 2), several other input parameters are needed. These include set parameters related to the steady-state model and weather parameters describing the boundary conditions of the RES (Table 3). The latter consists of the local solar irradiance ($q_{\text{sun}}$ in $W/m^2$) and the wind velocity ($v_{\text{wind}}$ in m/s). At the Varkenscampus, a weather station is installed that measures these at an hourly basis.

The RESs' hourly energy generating functions depending on the measured weather conditions are described by Eq. (1) to Eq. (5). Eq. (1) calculates the power $P$ [W] generated by a surface size $A$ [$m^2$] of PV panels. The model uses PV panels that generate 1 kWp per 7 $m^2$.

$$P_{\text{PV}} = q_{\text{sun}} \frac{A_{\text{PV}}}{7} \tag{1}$$

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**Table 3**: Chosen parameters to create the steady-state model.

| Parameter | Value |
|---|---|
| time step | 1 hour |
| simulated period | 1 year |
| boiler efficiency | 95% |
| low temperature heating | 40 °C |
| high temperature heating | 60 °C |
| low temperature nominal COP | 5 |
| high temperature nominal COP | 3.5 |
| COP nominal temperature | 17 °C |
| initial battery charge | 0 kWh |
| initial thermal storage temperature | 40 °C |
| maximal thermal storage temperature | 90 °C |

Eq. (2) describes the heat $Q$ [W] generating profile of solar thermal (ST) panels. These panels generate 4 times the solar irradiance per surface size of 7 $\mathrm{m}^2$, which results in an energy production of 500 $\mathrm{kWh/m^2/year}$.

$$Q_{\mathrm{ST}} = q_{\mathrm{sun}}\, 4\, \frac{A_{\mathrm{ST}}}{7} \tag{2}$$

For practical reasons, the generating profile of the photovoltaic thermal (PVT) panels is seen as a hybrid between PV and ST panels, relatively described by Eq. (3) and Eq. (4). They generate 80% of the electricity that PV panels would generate and 70% of the heat generated by the ST panels.

$$P_{\mathrm{PVT}} = 0.8\; q_{\mathrm{sun}} \frac{A_{\mathrm{PVT}}}{7} \tag{3}$$

$$Q_{\mathrm{PVT}} = 0.7\; q_{\mathrm{sun}}\, 4\, \frac{A_{\mathrm{ST}}}{7} \tag{4}$$

Finally the electricity generated by $n$ small wind turbines with each a power $P_{\mathrm{unit}}$ of 15kW is given by Eq. (5). The measured wind speed at a height of 10m is multiplied by a factor 1.3 to correct for the height of the wind turbine's blades, which is 15m. The nominal wind speed at which nominal power is reached, is 7.8 m/s.

$$P_{\mathrm{wind}} = n\; P_{\mathrm{unit}} \left(\frac{1.3\; v_{\mathrm{wind}}}{7.8\ \mathrm{m/s}}\right)^3 \tag{5}$$

### 3.1.3. Simulation methodology

Starting from the energy demand mentioned in section 3.1.1., the tool tries to satisfy this demand in subsequent order:

1. Fulfill the heat demand by using heat pumps, if any are installed.
2. If PV, ST, PVT panels and/or wind turbines are installed, their energy is used to its full capacity. Without heat pumps installed, their produced energy goes to the heating or electricity systems of the farm. If heat pumps are present, their energy is first provided to the heat pumps. If the energy production exceeds the total demand, the excess is put back onto the grid or lost in case of heat excess. If the heat demand is not fulfilled, electricity is taken from the grid if heat pumps are present, else the condensing gas boiler is used.
3. If storage systems are present, they are filled to their maximum capacity before sending electricity to the grid or losing heat.

Subsequently, an hourly energy balance of all 123,480 scenarios can be calculated.

### 3.1.4. Cost and emission functions

The energy consumption pattern is now known for every scenario. Next, the parameters necessary to calculate the investment cost, LCC and GHG emissions are introduced in this subsection.

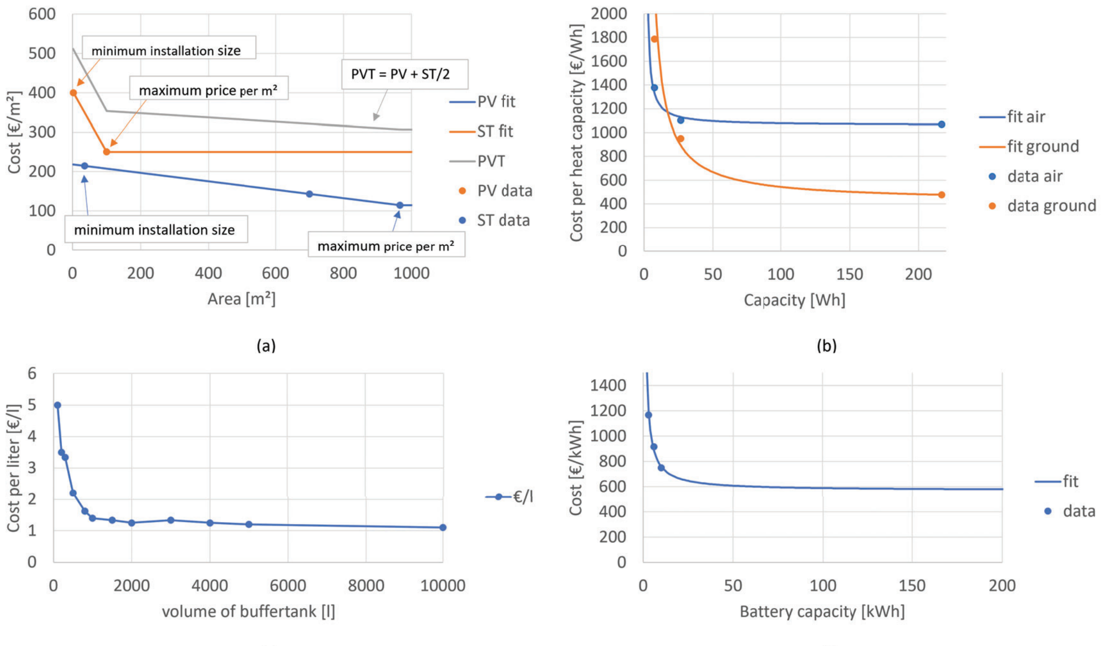
**Investment cost**
The investment cost is estimated from selling prices of local vendors. The condensing boiler and wind turbine are easiest to define since they exist as one unit. The prices chosen are:

- Condensing gas boiler: €15k (purchase price at Varkenscampus).
- Wind turbine: €60k (estimated from a commercial wind turbine [9]).

The other cost functions depend on the size of the installation. This phenomena can be attributed to the initial installation cost. They are represented by the functions in Fig. 4. To estimate these functions, the prices of several installation sizes were consulted. PV panel prices [10] and ST panel prices [11] were obtained from online sources. Prices of PVT panels are derived from these two and calculated with Eq. (6).

$$\mathrm{PVT} = \mathrm{PV} + \frac{\mathrm{ST}}{2} \tag{6}$$

The heat pump prices were obtained from De Win's dissertation [6]. The prices for thermal storage tanks [12] and batteries [10] were also obtained online.



(a) (b)

(c) (d)

**Figure 4**: Cost functions of the renewable energy sources with prices depending on the size, the functions are interpolated from local vendor prices with (a) price function of PV panels [10], ST panels [11] and PVT panels according to Eq. 6, (b) heat pump prices [6], (c) prices of thermal storage tanks (water) prices [12] and (d) battery price function [10].

### Life-cycle cost

The LCC takes into account the lifetime of the RES and their operational cost. When energy prices are high, it is self explanatory that autonomous energy generation would become more economical in the long run. The LCC is calculated using Eq. (7)

$$LCC = IC_0 + \sum_{i=0}^{n} \frac{EC_i + IC_i}{(1+r)^i} \tag{7}$$

The summation is done over a period of $n = 20$ years. Every year, the operational cost and potential replacement cost of the total combined system is calculated. $IC_0$ is the initial investment cost, calculated with the cost functions in Fig. 4. This cost reoccurs when the energy system's life is shorter than the 20 years, indicated in the sum by the term $IC_i$. In Table 4, an overview of the chosen lifetimes is given. Next in line is the operational cost, which is indicated by $EC_i$. It is calculated by multiplying the current energy tariffs and the yearly energy consumption resulting from the steady-state model. The energy tariffs can be found in Table 5 and were obtained from the VREG (Energy Regulator in Flanders) database [13]. At last, the reduction factor $\frac{1}{(1+r)^i}$ appearing in Eq. (7) represents the reduction in monetary value over the years. The parameter $r$ is the internal rate of return and is chosen to be 6%.

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**Table 4**: Lifetimes for the selected energy systems

| Energy system | Lifetime (years) |
|---|---|
| condensing gas boiler | 15 |
| PV panels | 25 |
| ST and PVT panels | 20 |
| heat pump | 20 |
| electrical battery | 8 |
| thermal storage tank | 20 |
| wind turbine | 20 |

**Table 5**: Energy tariffs in Flanders in 2022 [13].

| Energy source | Cost [€/kWh] |
|---|---|
| electricity cost | 0.5 |
| gas cost | 0.2 |
| injection cost | -0.15 |

**Greenhouse gas emissions**

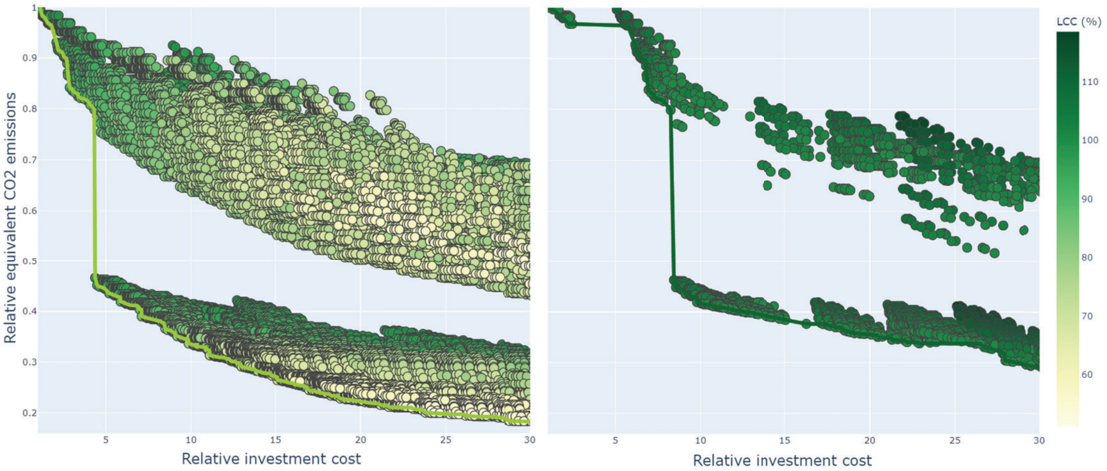
Just like the operational cost, the GHG emission is calculated by multiplying the energy demand from the steady-state model with the relevant parameters representing the GHG emissions. This is just a simple estimate without taking into account the GHGs emitted during the creation process of the RESs. For electricity from the grid and natural gas consumption, the equivalent $CO_2$ per kWh is given in Table 6 and were respectively obtained from the European Environment Agency [14] and Casasso et al. [15].

**Table 6**: Equivalent $CO_2$ emissions of the Belgian grid and the consumption of natural gas by a condensing boiler.

| Energy source | Effective $CO_2$ [kg/kWh] | |
|---|---|---|
| electricity grid | 0.20 | [14] |
| gas boiler | 0.25 | [15] |

## 3.2. Results

In Fig. 5 the results of the calculation are shown. All three parameters are represented in this graph (i.e. investment cost, LCC and GHG emissions). To better investigate the results, an interactive version (in Plotly) was made to observe which RESs are present in a selected scenario.



(a)

(b)

**Figure 5**: Scatter plots containing all 123,480 combinations from Table 2 with every dot representing a scenario for which the calculation was performed over one year, the results are expressed relative to the current installation which can be found at (1,1,1). In (a) results with a lower LCC compared to the current installation are plotted and in (b) those with a higher LCC, the optimal solutions can be found on the plotted lines (Pareto front).

A first observation is the separation into two clouds. The upper one has the most GHG emissions, but starts at the lowest investment cost compared to the lower cloud (only starting at a relative investment cost of 4 times the original scenario). This is due to a lack of heat pumps in the upper clouds, while the lower cloud represents all scenarios where heat pumps are present. To find the optimized solutions, the Pareto front was calculated for GHG emissions and investment cost for the selection of results with a lower relative LCC (Fig. 5a) compared to the original installation (in other words LCC $<$ 100%) and with a relatively higher LCC (Fig. 5b). This division was made to take into account the third parameter, since the Pareto front is only calculated with two parameters. The principle is based on Pareto optimality in which two parameters are compared. If one parameter improves, it is imposed onto the other parameter that it cannot degrade. If one parameter improves to the detriment of the other one, the solution is discarded. This results in a front along the minima of both parameters, as can be observed in Fig. 5. By walking down this Pareto front, the optimized combinations can be recognized. For a lower LCC, the order is as follows:

$$\textit{PV} > \textit{ST} > \textit{PVT} > \textit{thermal storage} > \textit{heat pumps} > \textit{electrical battery} > \textit{wind turbine}$$

and for a higher LCC:

$$\textit{PV} > \textit{electrical battery} > \textit{PVT} > \textit{ST} > \textit{thermal storage} > \textit{heat pumps} > \textit{wind turbine.}$$

For clarity, these Pareto fronts are visualized in Fig. 6.

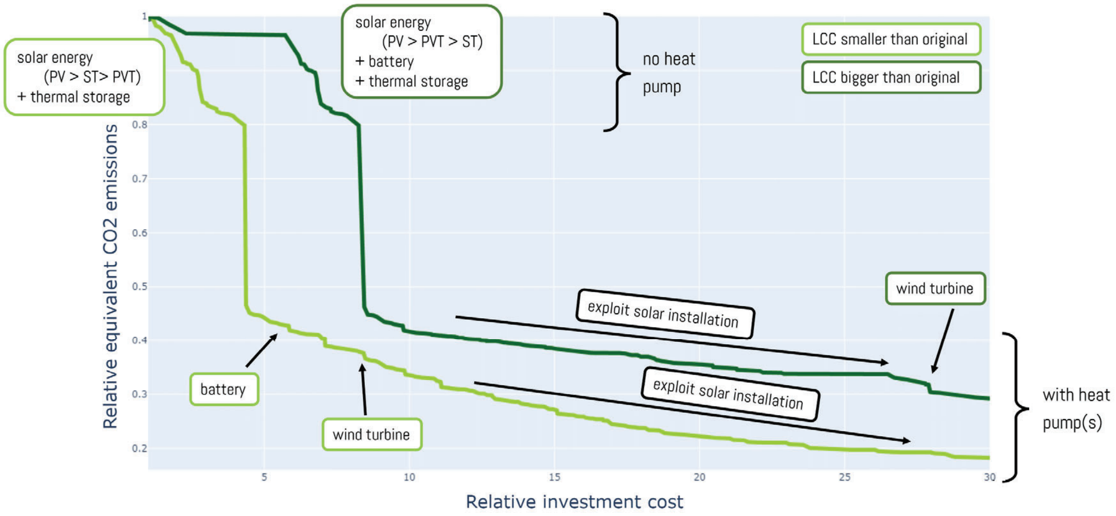


**Figure 6**: Pareto fronts representing an optimization of greenhouse gas emissions and investment cost, to take into account the third parameter (LCC) a separation was made between a relatively higher or lower LCC than the original installation at the Varkenscampus (natural gas boiler and grid connection), the boxes indicate the energy sources encountered in the configurations when walking along the fronts.

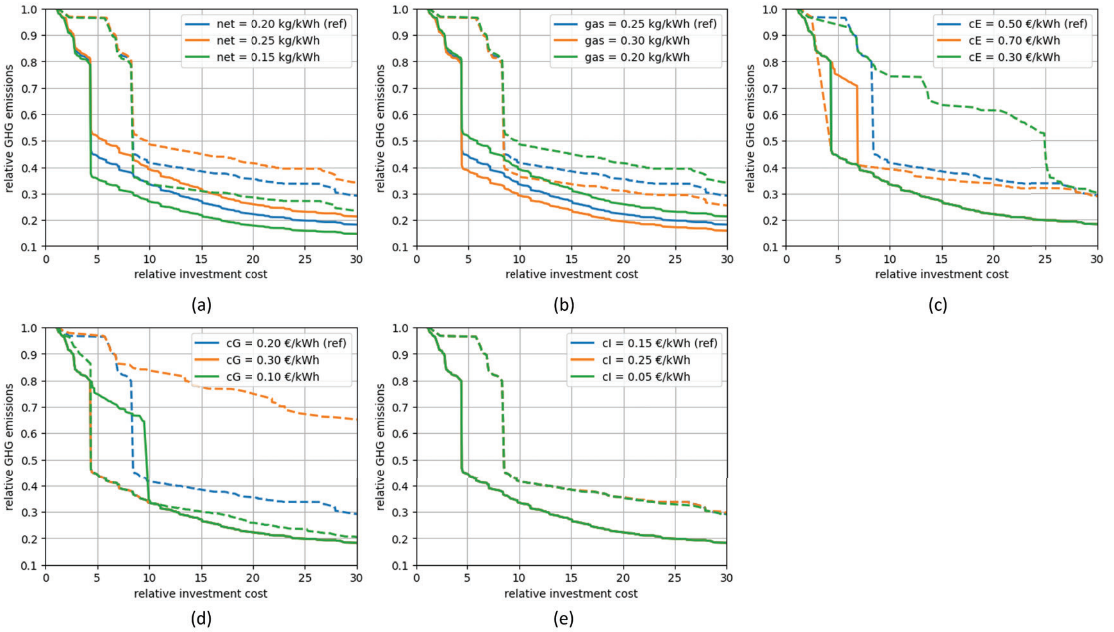
From these observations, it can be concluded that both Pareto fronts agree on installing solar panels first, preferably with heat production and storage. Taking this into consideration it seems that renewable energy systems are best integrated before installing a heat pump. Furthermore, installing a heat pump results into a large jump of 35% in the reduction of GHG emissions. Combining a heat pump with green energy, the GHG emissions are reduced by 55%. With the chosen parameters, the lower LCC Pareto front also results into the best case scenario for reducing GHG emissions compared to the higher LCC Pareto front. However, changing some parameters can cause the opposite to be true. This will be discussed in section 3.3. Batteries emerge sooner when walking along the front for higher LCC, which might be due to their short lifetime in the LCC calculation. Configurations with wind turbines appear last (starting at a relative investment cost of 8) on both fronts as their installation cost is the highest of all resources. However, they appear much sooner for lower LCCs indicating an economic advantage over longer periods.

### 3.3. Sensitivity analysis

A sensitivity study was made to see how the results behave when inserting different parameters. The changes are compared to a base case, for which the previously explained result is chosen. The adjusted parameters are shown in Table 7 with a variation in the relevant ranges. The influence of these variations on the optimized solutions can be derived from their influence on the Pareto fronts. This is shown in Fig. 7. The influence of the parameters corresponding to GHG emissions and energy costs will be discussed separately.

**Table 7**: Used alterations to the tweaked parameters.

| parameter | [unit] | ref. case | variation in relevant range | % |
|---|---|---|---|---|
| $CO_2$-eq. emissions of the grid | [kg/kWh] | 0.20 | ± 0.05 | 25 |
| $CO_2$-eq. emissions of the gas | [kg/kWh] | 0.25 | ± 0.05 | 20 |
| electricity price | [€/kWh] | 0.50 | ± 0.25 | 50 |
| gas price | [€/kWh] | 0.20 | ± 0.1 | 50 |
| injection cost | [€/kWh] | 0.15 | ± 0.1 | 67 |



(a) (b) (c)

(d) (e)

**Figure 7**: Influence of different parameters on the optimized solutions or Pareto fronts, the reference case from Fig. 5 is given in blue (in some cases, these blue lines are covered but they are the same everywhere), with a full line representing fronts with a lower LCC compared to the original scenario (where LCC = 1) and the dashed lines fronts with higher LCC, the studied parameters are (a) GHG emissions from the electricity network (b) GHG emissions from the natural gas boiler (c) electricity cost (d) gas price and (e) injection cost.

### Influence of the equivalent $CO_2$ emission

The variation of the equivalent $CO_2$ emissions for the electricity and natural gas causes a vertical shift in the dispersion of the 123,480 scenarios. Their effect is inversely proportional. While a lower GHG emission factor for the grid (Fig. 7a) drives the clouds together, the opposite is true for the GHG emission related to natural gas burning (Fig. 7b). Therefore, these parameters additionally influence the reduction in GHG emissions when installing heat pumps. In the reference case, a reduction of 35% was seen. A variation of 20% on the electricity emission factor can cause this jump to reduce or increase by 8%. Further analysis indicates that a relative variation of the gas emission factor has a bigger influence on the data than the grid emission factor. The LCC and investment cost are left unchanged.

### Influence of the energy prices

The variation in energy prices has a significantly higher effect on the results, especially on the Pareto fronts. Some variations even flip around the high and low LCC fronts, making configurations with a higher LCC more beneficial to reduce GHG emissions. This event occurs for high electricity prices (Fig. 7c: cE = 0.70 €/kWh) or low gas prices (Fig. 7d: cG = 0.10 €/kWh), causing a higher LCC for all scenarios containing heat pumps. The order encountered when walking along the Pareto fronts are the same as mentioned before (section 3.2.), but investing in a heat pump when electricity prices are high is detrimental for the LCC. This causes the front with higher LCCs to jump to heat pumps already at a lower investment cost than the front with lower LCCs. A higher investment cost is thus needed to make the reduction in GHG (by installing heat pumps) and simultaneously be beneficial to the LCC. When the electricity price is low (Fig. 7c: cE = 0.30 €/kWh) or the gas price high (Fig. 7d: cG = 0.30 €/kWh), the two Pareto fronts disperse until heat pumps no longer occur into the optimized

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configurations with a higher LCC (the dashed line never reaches into the lower cloud at acceptable investment costs). In such scenario, heat pumps come out on top both economically and ecologically. Further analysis indicates that the influence of electricity and gas prices on the LCC is opposite: a low electricity price causes a generally higher LCC and vice versa. Again, a relative variation of the gas price a bigger influence on the results than the electricity price. The injection cost barely has any influence (Fig. 7e), since this cost only occurs for overproducing configurations and is relatively small compared to the other costs.

It can be concluded that realistically occurring changes in energy prices result in different optimal solutions. This is not very convenient if the tool is to be used to calculate economically optimized configurations. A solution could be to better predict the LCC by improving Eq. (7) and introducing life-cycle assessments. On a more positive note, the jump in GHG emissions owing to heat pumps is consistent throughout all parameter ranges.

## 4. Conclusion

A tool was made to calculate the influence of different combinations of RESs on livestock barns. From the simulations some preliminary conclusions can be drawn. The installation of a heat pump is most effective on GHG emissions when green energy sources are already present. This causes a reduction in GHG emissions of 55% compared to the current gas boiler installation at the Varkenscampus (reference case). Due to their high investment cost, scenarios containing heat pumps only start occurring at relative investment costs of 4 times that of the gas boiler or higher. However, with moderate energy prices they are beneficial to the LCC except when electricity prices are high or gas prices are low. All optimized solutions agree on investing in solar energy first, preferably with heat production and storage. This is a sensible result, since the Varkenscampus and pig farms in general, require a lot of heat. The best investment would be a wind turbine resulting in scenarios with the lowest LCCs. Unfortunately, they only come into the picture at a relative investment cost of 8.

### Future work

The calculation tool requires further testing and fine-tuning. In the near future, two heat pumps, 50 m$^2$ PVT panels and a buffer tank of 800 liters will be installed at the Varkenscampus. This will be the calculation tool's first validation. Secondly, the tool needs to be expanded to other type of farms. As for the fine-tuning aspect, the cost and emission functions are pretty rough estimations at the moment. More sensitivity analyses must be performed on other parameters as well. It might be useful to connect the tool to energy price predictions on the web. Taking life-cycle assessments of the relevant RESs into account, would be an improvement as well. Many improvements are still to be made to the tool, but it already produces some sensible results. Fine-tuning, testing and adapting the tool to other farms can result into a positive contribution to the energy transition in livestock.

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## Nomenclature

### Abbreviations

| | |
|---|---|
| *RES* | renewable energy source |
| *GHG* | greenhouse gas |
| *LCC* | life-cycle cost |
| *PV* | photovoltaic |
| *PVT* | photovoltaic thermal |
| *ST* | solar thermal |
| *COP* | coefficient of performance |

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