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ABBREVIATIONS

AC	:	Alternating Current
AIMSFS	:	After Interventions Medium Sized Fan System
AISSFS	:	After Interventions Small Sized Fan System
AMS	:	Automatic Milking System
ATES	:	Aquifer Thermal Energy Storage
BEV	:	Battery Electric Vehicle
BioCNG	:	Biogas-Based Compressed Natural Gas
BOM	:	Bill of Materials
BTES	:	Borehole Thermal Energy Storage
CHP	:	Combined Heat and Power
CNG	:	Compressed Natural Gas
EIC	:	Environmental Impact Category
EICI	:	Environmental Impact Category Indicator
FU	:	Functional Unit
FYAIS	:	First Year After Intervention(s) System
HP	:	Heat Pump
HVAC	:	Heating Ventilation Air Conditioning
LC	:	Life Cycle
LCA	:	Life Cycle Assessment
LCIA	:	Life Cycle Impact Assessment
LPG	:	Liquefied Petroleum Gas
PV	:	Photovoltaics
PVT	:	Photovoltaic-Thermal
RS	:	Reference System
SB	:	System Boundary
SES	:	Single Environmental Score

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

RES4LIVE is an H2020-funded project whose strategic objective is to develop and bring into the market integrated, cost-effective, and case-sensitive renewable energy systems (RES) solutions toward achieving fossil-free livestock farming.

Within the framework of WP5: "Technical, socio-economic and environmental assessment" the impact of the solutions proposed and applied were assessed technically, economically and environmentally to judge with scientific evidence the prospects of replicability.

Deliverable 5.3: 'Environmental Assessment Report' is part of Task 5.3: Environmental Assessment. The primary activity involved the development of life cycle (LC) models and inventories using site-specific data collected from the four pilot farms, both before and after the RES4LIVE interventions. This data focused on environmental aspects such as material use, energy consumption, water use, and solid waste generation, as well as emissions to air, soil, and water, both on- and off-field. An extensive Life Cycle Impact Assessment (LCIA) was conducted to aggregate the LC inventory into measurable environmental impacts. Additionally, the results from Tasks 3.4 and 5.1 were used to analyse energy flows and material requirements. Special attention was given to identifying hotspota - processes or points that significantly contribute to emissions - to quantify the positive effects of the proposed technologies and energy efficiency measures. In all cases, the key emissions were quantified and compared against those from conventional fossil fuel-based solutions.

Utilising primary data from both pilot farms and the technology developer of the consortium, as well as background data available in the literature and established databases, dedicated LCA models were developed for each system.

The results provide valuable insights into their environmental impact across different livestock facilities after one year of operation. In the GOLINELLI hog barn, there was a slight increase in environmental impact due to higher electricity consumption and material use. In contrast, the GOLINELLI nursery barn saw a notable reduction in its impact, mainly because of eliminating LPG and using more renewable energy for heating the barn. The EV ILVO farm showed improvements in its environmental performance due to reduced fossil fuel use and the removal of natural gas for heating the building. However, the AUA poultry farm experienced an increase in environmental burden despite several positive changes. The addition of a BioCNG plant at the LVAT farm showed promising results while highlighting the trade-offs between reducing fossil fuel use and the potential rise in climate change impact category indicators. Overall, these findings suggest that new technologies can positively affect environmental outcomes in intensive livestock operations while highlighting aspects that require further consideration.

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1 INTRODUCTION

This deliverable, D5.3: 'Environmental Assessment Report,' presents the results of T5.3 activities, which focused on evaluating the environmental impact of the RES4LIVE integrated solutions. The main task was to develop life cycle (LC) models and inventories using site-specific data collected from the four pilot farms, both before and after the RES4LIVE interventions. This data included information on material use, energy consumption, water use, solid waste generation, and emissions to air, soil, and water, both on-site and off-site.

Detailed Life Cycle Impact Assessments (LCIA) were carried out to translate the LC inventory into measurable environmental impacts. The findings from Tasks 3.4 and 5.1 were also used to analyse energy flows and material needs. A key focus was on identifying "hotspots"—the processes or areas contributing the most to emissions—to measure the benefits of the proposed technologies and energy efficiency measures. In all cases, key emissions were quantified and compared to those from conventional fossil fuel-based systems.

Using primary data from both the pilot farms and the consortium's technology developers, along with background data from literature and established databases, specific LCA models were created for each system.

The deliverable is structured as follows: Section 2 outlines the methodological approach, detailing the goal and scope of the study, the functional units (FU) and system boundaries (SB) used in each case, the data collection and modelling procedure, as well as the main limitations encountered. Sections 3, 4, 5, and 6 are dedicated to the presentation of the impact assessments for the pilot farms—GOLINELLI (swine), EV ILVO (swine), AUA (poultry), and LVAT (dairy cattle), respectively—covering results, key findings, and discussions. Section 7 concludes with a summary of the key outcomes and recommendations for future applications of the technologies in similar livestock farming environments.

2 METHODOLOGY

In general, Life Cycle Assessment (LCA) is a systematic analysis of a product, service, or system's impact on the environment. It can consider the stages from raw material extraction, manufacturing, distribution, and usage, to end-of-life treatment. The general LCA framework, as established by the ISO14040 standard, includes the following main phases (Figure 1):

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

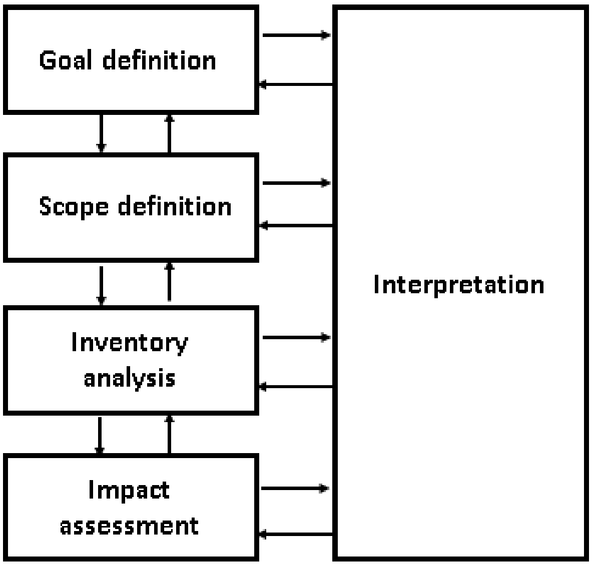

Figure 1. The LCA framework.

All inventories have been developed in Word documents and Excel spreadsheets for the chosen life-cycle stages. The impacts are assessed at midpoint and endpoint levels by applying the Environmental Footprint 3.1 as a Life Cycle Impact Assessment (LCIA) method, in SimaPro software (SimaPro 9.6.0.1 version). The measurement methods are aligned with ISO 14040:2006 and ISO 14044:2006.

2.1 Goal and scope

The intended application of the LCA – in the framework of the RES4LIVE project – is to understand the effect of implementing specific Renewable Energy Sources (RES) technologies interventions on the economic (see Deliverable 5.2) and environmental performance of different - mostly livestock - systems. This essentially means that this deliverable (as well as Deliverable 5.2) focuses on the differences between midpoint and endpoint indicators for the environmental performance (comparing the status before and after the implementation of the technologies), which are directly driven by the implementation of the technologies examined in the project, to highlight the potential positive or negative effects. While replacing conventional fossil-energy-based systems with RES-based ones is the main goal of the project, the reasons for assessing the effect on the environmental performance are multifaceted:

- Assurance that the transition to renewable energy is both effective and (economically and environmentally) sustainable.
- Evaluation of trade-offs to ensure that the implementation of the examined technologies has a net positive impact on the economic and environmental performance.
- Provide input to stakeholders who devise strategies that promote (economic and environmental) sustainability.
- Gain more insights into a less-studied area of the literature.

It is intended that both the technical and non-technical public will benefit from the work. More specifically, the target audience is researchers, livestock farmers, and decision-makers involved in both livestock and energy sectors. By making a comprehensive LCA, potential advantages and shortcomings will be identified and minimised in future applications.

2.2 System boundary (SB) and Functional unit (FU)

The system boundary (SB) defines the extent of the analysis, specifying which processes and stages of the technical system are included. In addition to the system boundary, geographical and temporal boundaries are established to delineate the spatial and time-related scope of the study (Curran, 2017). The functional unit (FU) in an (economic and environmental) LCA study represents the quantifiable performance of a product or system, serving as the reference for all inputs and outputs in the analysis. Its clear definition is particularly critical in comparative LCAs to ensure consistency and comparability between systems.

As outlined in the following sections, the SB and FU are determined based on the specific impact each integrated RES system has on the operation of each pilot farm. The pilot farms considered in the RES4LIVE project are:

1. The commercial swine farm GOLINELLI (Italy)
2. The experimental swine farm ILVO (Belgium)
3. The experimental poultry farm of the AUA (Greece)
4. The experimental dairy cattle farm LVAT (Germany)

For cases where interventions directly influence specific mid- or final-product outputs at the facility (as seen with the GOLINELLI, ILVO, and AUA farms), a cradle-to-livestock house gate approach is applied for assessing the environmental performance, with the FU defined as 1 kg of product (e.g., live pigs, or eggs) at the livestock house gate. Conversely, when the installed system's operation does not distinctly affect a particular animal product (as observed at the LVAT farm), a cradle-to-sub-system gate approach is used. For example, in the case of the BioCNG unit (sub-system), the FU is defined as 1 kg of biomethane upgraded from biogas (i.e. the product outflow at the gate of the BioCNG sub-system).

The compared systems are evaluated based on their equivalent functions during two periods: prior to the RES systems' installation (2020-2022 data) and after their implementation (2023-2024 data). The geographical scope of each study is pilot study-specific, with a temporal boundary established for 1 year of operation. Estimating the first year of the technologies' normal operation was feasible in almost all pilot farms, using data from the installed sensors for monitoring crucial parameters, such as the annual electricity consumption in the livestock houses; this data was either directly available from measurements or extrapolation to one-year of operation was performed from the data available[1]. It is important to highlight that the total impact of each examined technology is allocated over its entire lifetime. The system boundary follows a cradle-to-sub-system-gate scope, encompassing the technology supply chain processes such as mining, transportation, production, installation, and operation.

Where allocation was unavoidable, the economic and environmental burden was distributed based on physical relationships (e.g. electricity and heat production in the CHP unit at LVAT pilot farm) or economic values (e.g. co-products at the swine housing gate at ILVO and GOLI pilot farms).

2.2.1 SB 1: Cradle-to-farm gate (GOLINELLI, ILVO, AUA)

As described in the previous section, in the cases of GOLINELLI, ILVO, and AUA pilot farms, the selection of cradle-to-livestock-housing-gate SB has been based on what is indicated in Figure 2, Figure **3**, and Figure **4** because the RES4LIVE interventions influence the operation of the livestock houses and reflect on the livestock live-weight product outputs from these houses.

In the GOLINELLI pilot farm the project's interventions concern two separate buildings: the nursery and hog barn of the farm. Therefore, two different LCA models have been developed. The blurred parts in Figure 2 illustrate the systems substituted by the RES4LIVE technologies. In the nursery barn, an integrated PVT/ BTES/ Heat pump system substitutes an existing LPG boiler, while the envelope of the hog barn has been upgraded by installing new automatic windows. Both barns were further equipped with a smart climate control system in the context of RES4LIVE.

[1] For more information, refer to deliverables D5.:1 "Technical assessment and validation of the numerical platform", and D4.3: "Report with the results obtained on energy and production performances of RES and energy efficiency solutions".

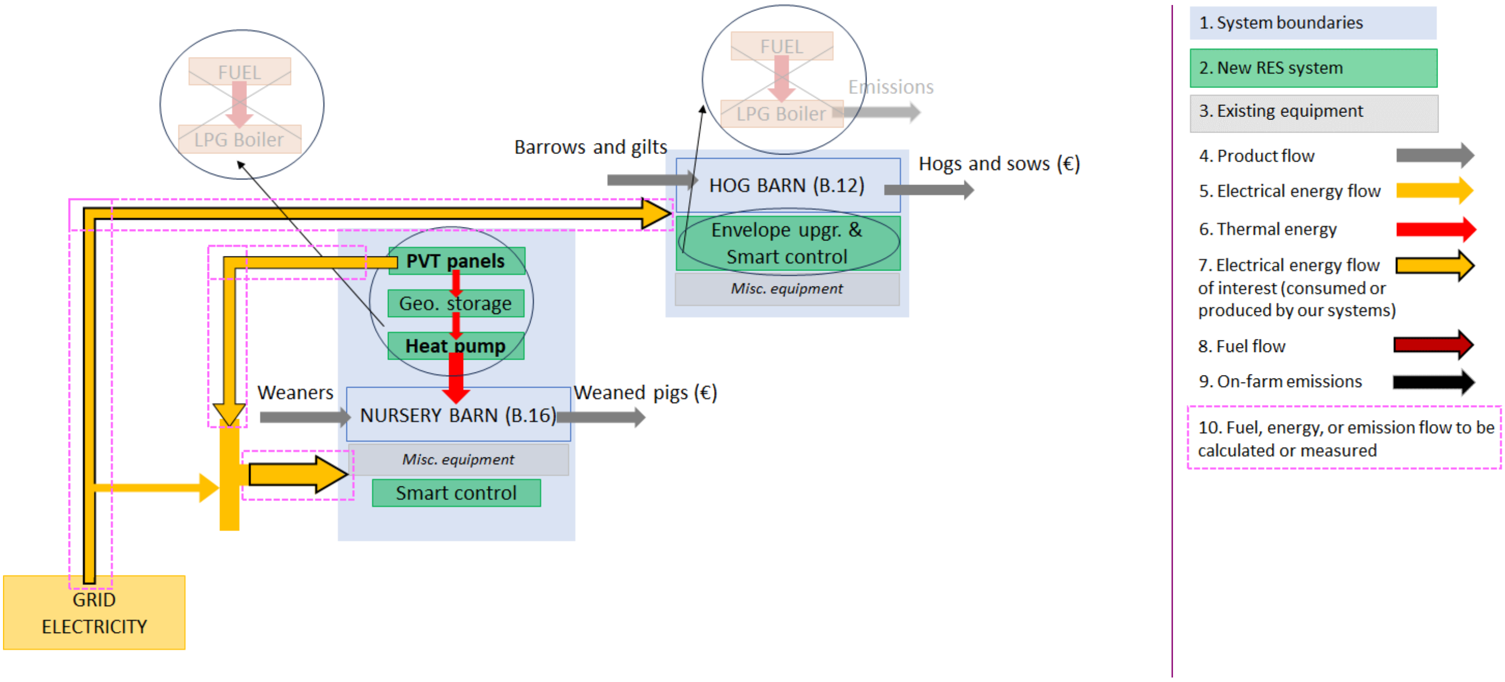

Figure 2. RES4LIVE interventions indicating the cradle-to-livestock-housing-gate system boundaries (SB) in the GOLINELLI case.

ILVO pilot farm consists of an undivided building consisting of multiple compartments hosting pigs of different productive stages. In its case, a natural gas boiler has been substituted by a PVT/ Heat pump system accompanied by a short-term thermal storage tank (Figure 3), providing heating and domestic hot water to the whole facility. Again, the blurred parts illustrate the systems substituted by the RES4LIVE technologies.

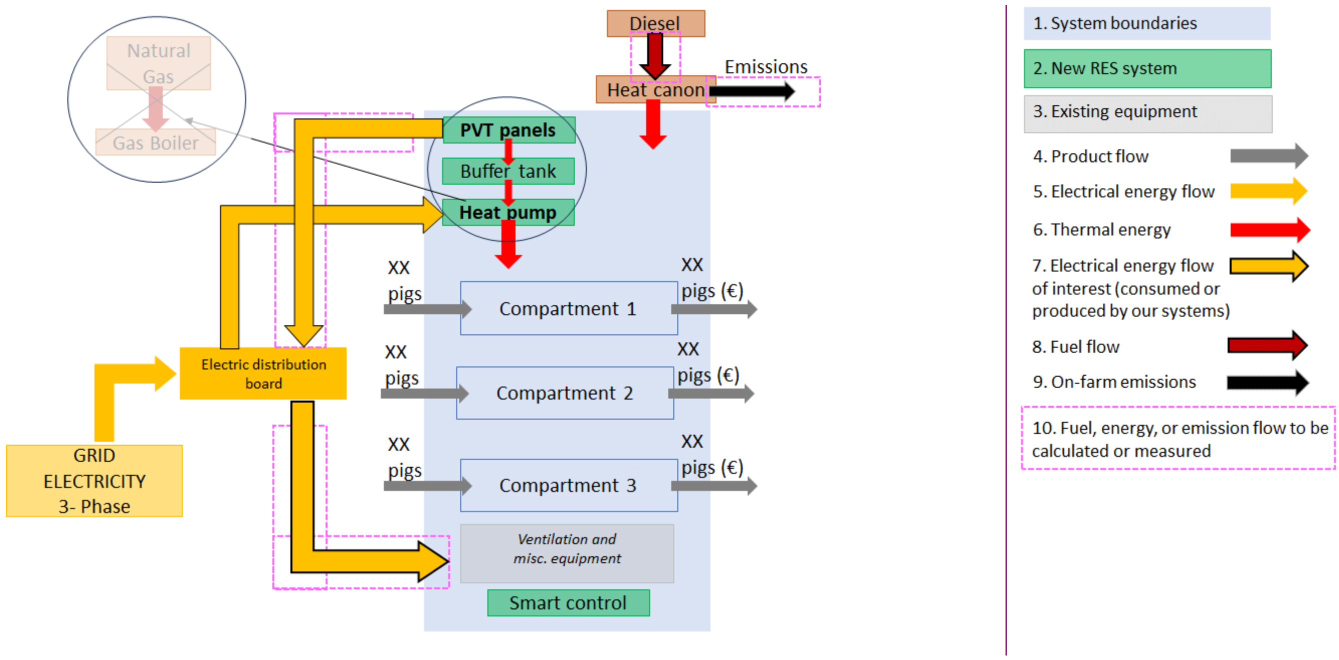

Figure 3. RES4LIVE interventions indicating the cradle-to-livestock-housing-gate system boundaries (SB) in the ILVO case.

The AUA pilot farm building is divided into two compartments: one hosting pullets and the other laying hens. No system has been substituted as in the two previous cases. All interventions (PV system, Heat pump, LEDs, Smart control) are supplemental in order to enhance animal welfare while covering part of the electrical energy consumption (Figure 4).

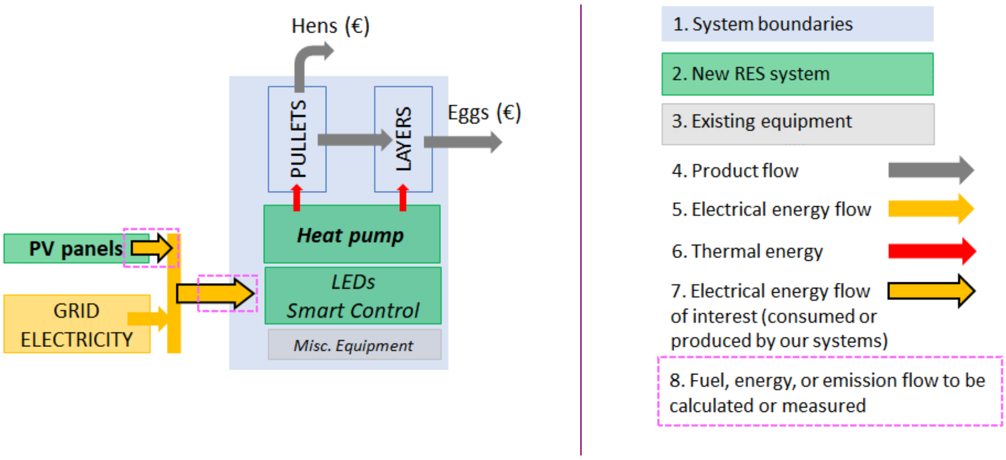

Figure 4. RES4LIVE interventions indicating the cradle-to-livestock-housing-gate system boundaries (SB) in the AUA case.

2.2.2 SB 2: Cradle-to-sub-system gate (LVAT)

In the case of the LVAT pilot farm where the installed RES system's operation (Figure 5) does not distinctly affect a particular animal product, but rather other agricultural and bio-energy/fuel operations at the farm level, we used a different approach, focusing on three different subsystems:

1. The PVT system, installed to provide hot water to the existing electric boiler
2. The BioCNG unit, developed to upgrade the biogas produced by the existing biogas plant
3. The modified diesel tractor for biomethane use, used for on-farm daily activities

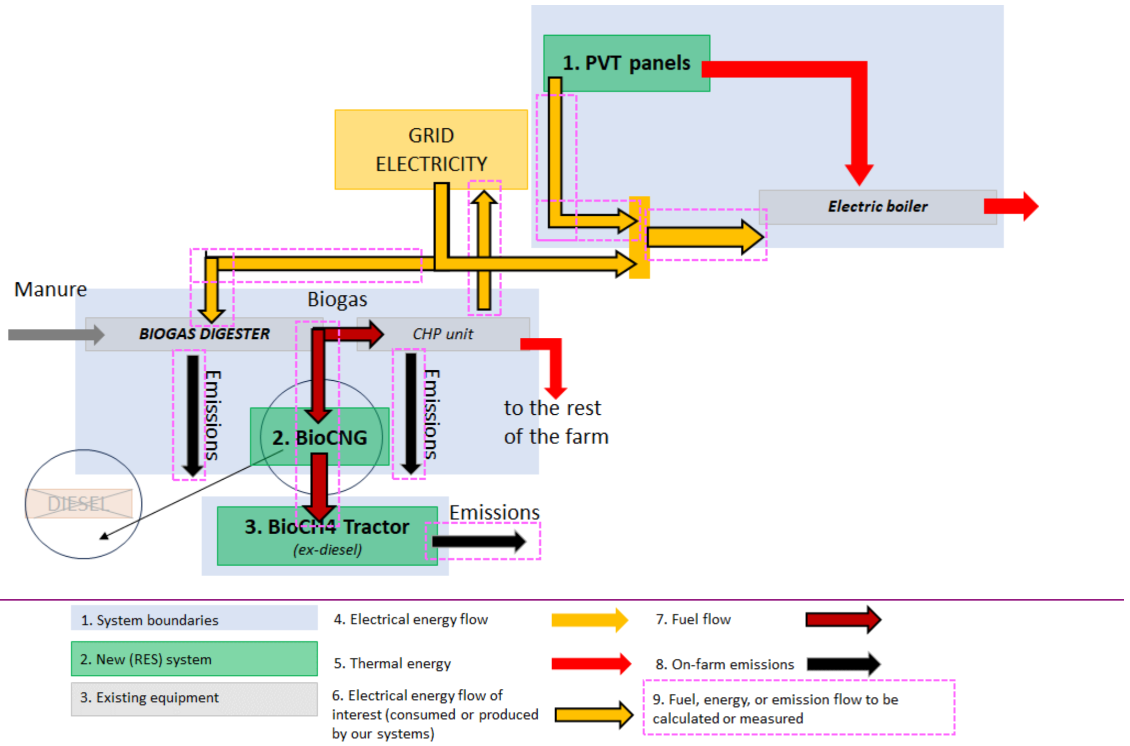

Figure 5. RES4LIVE interventions indicating the cradle-to-sub-system-gate system boundaries (SB) in the LVAT case.

2.2.3 Functional units

The functional units (FU) were defined to agree with the major product outflows of the examined systems. Table 1 collects the functional units for all the systems examined.

Table 1. Functional Units (FUs) of the systems examined.

PILOT FARM - SYSTEM	FUNCTION	FUNCTIONAL UNIT (FU)
GOLINELLI commercial, swine farm - Hog Barn (B.12)	Mature sow live-weight sale	1 kg of sow at the hog barn gate
GOLINELLI commercial, swine farm - Nursery Barn (B.16)	Weaned piglets live-weight sale	1 kg of weaned piglet at the nursery barn gate
ILVO experimental, swine farm	Finished pigs live-weight sale	1 kg of finished pigs at the livestock-housing gate
AUA experimental, poultry farm	Sale of eggs	1 kg of eggs at the livestock-housing gate

Table 1. Functional Units (FUs) of the systems examined (continued).

PILOT FARM - SYSTEM	FUNCTION	FUNCTIONAL UNIT (FU)
LVAT dairy cattle farm - Electric boiler	Provision of hot water	1 kWh of heat at the gate of the electric boiler
LVAT dairy cattle farm - BioCNG unit	Production of biomethane	1 m^3 of BioCNG at the gate of the BioCNG unit
LVAT dairy cattle farm - Tractor	Provision of agricultural operations (mostly transport of feed materials to dairy cattle)	1 hr of agricultural operations' provision

2.3 Data collection procedure

Data collection was carried out in two distinct phases; the first phase (RP1-RP2) focused on gathering foreground data on the reference systems, specifically the pilot farms prior to the RES4LIVE interventions. For the years 2020-2022, the data acquired could be included in the following categories:

- Products
- Inputs from nature
- Inputs from technosphere
- Animal capital
- Manure management
- Heat and electricity
- Equipment and machinery

The second phase (RP2-RP3) involved: (i) updating the aforementioned questionnaires for the years 2023 and 2024, and (ii) collecting data related to RES (Renewable Energy Systems) technologies. This latter aspect was considered critical for conducting a detailed environmental impact assessment of the systems including the interventions. It emphasised the development of comprehensive Bills of Materials (BOMs) for each RES unit or system developed and implemented within the framework of the project.

Foreground data related to on-farm operations was gathered through questionnaires specifically designed for this purpose, with the collaboration of the RES4LIVE partners responsible for data collection at each farm. The data was collected by GOLINELLI/UNIBO, ILVO/UGENT, AUA, and LVAT/ATB, and analysed by AUA. Foreground data concerning the RES systems was collected via dedicated questionnaires distributed to the developers of the innovative systems, including:

- ATB – for the BioCNG unit and barn cooling system[2] in the LVAT farm
- MG Sustainable – for the PVT systems in GOLINELLI, ILVO, and LVAT farms
- PSYCTOTHERM – for the heat pump in the GOLINELLI, ILVO, and AUA farms
- CRMT – for the adapted biomethane tractor in the LVAT farm
- PLEGMA – for the smart control systems in all four pilot farms
- UNIBO – for the BTES system in the GOLINELLI farm
- AUA – for the PV and LED systems in the AUA farm

To ensure consistency in data collection, all teams involved worked closely together, supplementing their efforts as needed with email exchanges and online meetings to address specific issues.

Background data related to both pilot farm operations and RES systems (such as raw materials extraction, processing, manufacturing, assembly, and installation) was collected from equipment manufacturers, available, international databases for background LCA data (such as the Ecoinvent and the Agribalyse databases), and relevant literature.

2.3.1 Data quality requirements

All primary, numerical data for compiling the farm-level inventory datasets for all pilot farming systems of interest (both reference and after the operation of the RES4LIVE technologies) can be considered of high quality, regarding site specificity, time and technology representativeness, as the data was provided directly by the managers of these farming systems.

The data used in this study for the compilation of the inventory datasets for the RES4LIVE technology inputs, including technical specifications and construction details of the system components, were primarily sourced from unit developers and component manufacturers. In cases where primary data were unavailable or incomplete, secondary data from scientific publications, theses, and other literature were used to supplement specific aspects of the systems under study.

When available data were insufficient, estimates were derived using a combination of literature, the Ecoinvent database v3.1, and expert judgement from the RES4LIVE Consortium members. The modelling of system components (e.g., raw materials, processes, etc.) was performed using Ecoinvent database v3.1, which is widely recognized for its maturity and reliability. Therefore, the data used in this study are considered to meet appropriate quality standards.

It is important to highlight that for inputs such as compound feed mixes and bedding materials and for outputs such as livestock-related emissions (i.e. ammonia, nitrous oxide and methane emissions from in-house manure excretion and handling for the cases of ILVO, GOLINELLI and AUA pilots) that are not expected to be affected from the operation of the RES4LIVE technologies or there could be an indirect effect which could not be measured in the context of the project, secondary data[3] was

[2] The barn cooling system is not included in this report. Since it is a new system, its effects could not be compared with any previous setup. Therefore, the study focused solely on the environmental impact of the system itself. The results will be included in the RP3 Technical Report.

[3] In LCAs whose goal is to estimate the environmental performance of livestock systems, using primary - higher quality- data for compound feed inputs and livestock related emissions is of crucial importance, as their contribution to the environmental performance of the system is high.

used. This data was not altered in the systems before and after the installation and operation of the RES4LIVE technologies.

2.4 Modelling process

The goal of the environmental assessment within the RES4LIVE project is to compare and highlight the differences in the environmental performance of two systems: one before, and one after the installation and operation of the innovative RES systems. The SimaPro 9.6.0.1PhD software was used for compiling the LCA models for the systems of interest both before and after the installation and operation of the RES4LIVE technologies.

2.4.1 “Reference” model

Exhaustively modelling the buildings of interest in massive farms (e.g., GOLINELLI, ILVO) would be highly time- and resource-consuming[4]. Moreover, since the goal of the environmental assessment, and the project itself, is to showcase the potential benefits of introducing RES technologies, the assessment focused on the inputs and outputs of the systems of interest which were most affected by the project’s interventions. Due to the nature of these interventions, electrical energy and fuel consumption, as well as the respective on-farm emissions from fuel consumption, are impacted far more than, for instance, feed input and livestock-related emissions due to, e.g., manure handling.

For inventory compilation when modelling the reference system, attention was given to the farm’s size, specific characteristics, and animal stock. Other inputs (e.g., feed, water, chemicals, etc.) or outputs (e.g., manure emissions, etc.) were also considered, using background data from various LCA databases (e.g. Agribalyse v3.1.1, Ecoinvent v.3.1) to approximately, yet reliably, model the supply chain ending at the system of interest. Contrary, to complete the on-farm LCA datasets, emphasis was put on extracting the annual electricity, heat and fuel consumption and production data when relevant for the systems of interest (previously submitted deliverables of WP3 and WP4 and questionnaires replied to by the responsible partners).

2.4.2 “After interventions” model

To “After interventions” model the RES interventions in SimaPro software, a dedicated Bill of Materials (BOM) was first created for each unit or system in collaboration with the project partners responsible for their design and manufacturing. The draft dataset for each unit was organised by component, with the following information included for each:

- Quantity
- Model and/or Type, special characteristics
- Material
- Mass

[4] In the case of the AUA pilot farm, because of its small size, a more detailed modelling of inputs and emission was possible.

- Manufacturer's name
- Origin

Examples of these datasets can be found in the Annex (Section A.5). The data were then further analysed to map each sub-component to the appropriate Ecoinvent processes, reflecting the raw materials and energy required for their conversion to (semi)finished products. Subsequently, Ecoinvent processes for assembling each component and/or unit as a whole were incorporated. The transport of the final RES system was also considered. In cases where uncertainties existed (e.g., the origin of sub-components or manufacturing methods), European-level background data of the Ecoinvent processes were utilised. The complete BOMs for each technology can be found in Annex A "RES4LIVE SYSTEMS BILLS OF MATERIALS (BOM)".

Table 2 presents examples of the Ecoinvent processes selected to build the datasets for each technology.

Table 2. Examples of Ecoinvent process, background datasets selected to compile the datasets for each technology.

COMPONENT, PROCESS, OR LIFE-CYCLE STAGE	ECOINVENT PROCESS
Raw or semi-finished material	Steel, low-alloyed, hot rolled {GLO}| market for steel, low-alloyed, hot rolled | Cut-off, U
	Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U
Material processing	Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U
	Casting, brass {GLO}| market for casting, brass | Cut-off, U
Material transformation and/ or Assembly	Metal working, average for steel product manufacturing {RER}| metal working, average for steel product manufacturing | Cut-off, U
	Electricity, medium voltage (Europe without Switzerland)| market group for | Cut-off, U
	Heat, district or industrial, natural gas (Europe without Switzerland)| heat production, natural gas, at industrial furnace >100kW | Cut-off, U
Final products (adapted to each RES unit's characteristics)	Photovoltaic panel, single-Si wafer {GLO}| market for photovoltaic panel, single-Si wafer | Cut-off, U
	Inverter, 2.5kW {GLO}| market for inverter, 2.5kW | Cut-off, U
	Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U
	Tube insulation, elastomere {GLO}| market for tube insulation, elastomere | Cut-off, U
	Pump, 40W {GLO}| market for pump, 40W | Cut-off, U

Table 2. Examples of Ecoinvent process, background datasets selected to compile the datasets for each technology (continued).

COMPONENT, PROCESS, OR LIFE-CYCLE STAGE	ECOINVENT PROCESS
Transportation	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U
Custom made processes (not readily available in the Ecoinvent database)	Refrigerant R125 {GLO-CN}| market for refrigerant R125 | Cut-off, U
	Refrigerant R32 {GLO-CN}| market for refrigerant R32 | Cut-off, U

After completing the datasets specific to the RES systems, they were integrated into the pre-existing "Reference Model" of the farming system, as additional inputs, considering their expected lifetime. The resulting "After Interventions" farm-level model, further included all modifications to product, electricity, heat and fuel emissions outputs as well as to electricity and fuel inputs caused by the annual operation of the RES4LIVE technologies.

2.5 Main limitations and assumptions

An LCA study typically includes all materials and energy inputs associated with the life cycle of the product or service being analysed, within the defined system boundaries. However, due to resource and data constraints, assumptions and approximations were necessary to model certain processes.

When modelling the farm facilities and operations to create the “reference systems” (before the project's interventions), a simplified approach was adopted. Not all elements of the facilities were included due to data and resource limitations. However, since the primary objective was to estimate the net environmental impact of the interventions through a comparative analysis, this simplification was considered acceptable, as this comparison is basically affected by: 1) the product, electricity, heat and fuel emissions’ outputs, 2) the electricity and fuel inputs caused by the annual operation of the RES4LIVE technologies and 3) the technologies’ inputs themselves, flows that were modelled in detail in this study.

Given the focus on innovative renewable energy systems (RES), the project partners emphasised the need for a detailed breakdown of components. This was essential for achieving reliable results and developing a comprehensive dataset for such applications that could be utilised by the scientific community. However, data collection for each part of the pilot farm system proved time-consuming due to the diversity of sources involved.

The key assumptions made in this study are as follows:

- Transport (RES4LIVE technology LCA models): Due to significant data gaps, transport related to the assembly of individual system components was not considered. For raw materials, approximate transport distances were calculated and embedded in the generalised "market" processes from the Ecoinvent database.

- Dataset Adjustments (RES4LIVE technology LCA models): Where necessary, modifications were made to Ecoinvent datasets to ensure the processes were as representative as possible for the specific components under consideration.
- Farm-level System Modelling: The modelling of system components, including raw materials and manufacturing processes, was simplified. The most relevant and representative processes from the Ecoinvent database were selected for this purpose. Specifically, regarding the fuel and electricity inputs, the European or global market mixes and the country mixes as available in the Ecoinvent database, were respectively used.

2.6 Environmental indicators

Midpoint and endpoint environmental life cycle impact assessment was conducted in accordance with the Product Environmental Footprint method of the EU (Environmental Footprint 3.1, as embedded in the SimaPro software). At the midpoint level, this method includes the estimation of 16 environmental impact category indicators (EICIs) (Table xx). At the endpoint level, an overall weighted, single environmental score (SES) is estimated after the implementation of normalisation and a weighting step (weighting factors in Table 3).

Table 3. The Environmental Impact Category Indicators (EICIs) of the EU Environmental Footprint Method and the weighting factors (single score estimation).

A/A	ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	WEIGHTING FACTOR	RANKING ACCORDING TO WEIGHTING FACTOR
1	Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	0.2106	1
2	Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	0.0631	7
3	Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	0.0501	9
4	Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.0478	10
5	Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	0.0896	2
6	Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	0.0184	16

Table 3. The Environmental Impact Category Indicators (EICIs) of the EU Environmental Footprint Method and the weighting factors (single score estimation).

A/A	ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	WEIGHTING FACTOR	RANKING ACCORDING TO WEIGHTING FACTOR
7	Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	0.0213	14
8	Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.062	8
9	Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	0.028	13
10	Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	0.0296	12
11	Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	0.0371	11
12	Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	0.0192	15
13	Land Use	Soil quality index (SQI)	Pt	0.0794	5
14	Water use	m^3 water eq. deprived (WU)	m^3 depriv.	0.0851	3
15	Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	0.0832	4
16	Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	0.0755	6

2.6.1 Correlation of environmental impact categories to animal welfare

Animal welfare indicators (such as welfare-related stress, animal behavioural aspects, ethical concerns regarding animal treatment) are not explicitly included in the EU Environmental Footprint (EU-EF) Life Cycle Impact Assessment (LCIA) method or in any other LCIA method currently available. Thus, there is no direct correlation of the environmental impact categories (EICs) and indicators

(EICIs) to animal welfare indicators. However, several midpoint Environmental Impact Categories (EICs) in the EU-EF method indirectly affect animal welfare. The most relevant ones include Land Use, the categories relating to air and water pollution (e.g. Acidification, Eutrophication) and Climate Change.

Land Use: Agricultural expansion and land conversion disrupt ecosystems, affecting wild animal populations and livestock welfare in extensive farming systems.

Water and air pollution: Industrial animal farming contributes to water contamination (e.g., nitrate pollution) and air pollution (e.g., ammonia emissions), which impact both human and animal health.

Climate change: Rising temperatures and extreme weather events increase heat stress in livestock, affecting productivity and overall well-being.

While integrating animal welfare into LCA methodologies would be theoretically possible, there are several challenges to be addressed:

1. **Lack of standardized metrics**: Animal welfare is often assessed through qualitative indicators (e.g., behavioral observations, ethical concerns), which are difficult to quantify in LCIA models.
2. **Variability across farming systems**: Animal welfare standards differ between intensive farming, organic farming, and extensive systems, making generalizations difficult.

Nevertheless, there are clear opportunities in such integration initiatives:

1. **New impact categories and indicators**: Adding welfare-related stress indicators into existing LCIA frameworks could allow for direct measurement.
2. **Multi-criteria decision approach**: A hybrid approach combining LCA with animal welfare assessments could improve decision-making in sustainable agriculture.
3. **Policy and labeling initiatives**: Expanding eco-labeling systems to include animal welfare scores would encourage producers to adopt both environmentally and ethically responsible practices.

2.7 Environmental Performance per Functional Unit

To provide a basis for comparison of the estimated results, it was selected to present values of each midpoint environmental indicator per functional unit for systems which could be considered as reference to the systems studied.

The EICI values of an average pig breeding production system in Europe focusing on the sows' live-weight output (i.e. per kg of sow live-weight output), as modelled in the Agri-footprint database are shown in Table 4. In Table 4, the EICI values per kg of swine live-weight produced on an average swine farming system in Italy, as modelled in the World Food LCA database are further presented. For both systems, cradle-to-farm-gate system boundaries were applied. These EICI values could be considered as reference environmental performance metrics for the GOLINELLI-Hog Barn system.

Table 4. The Environmental Impact Category Indicators (EICIs) per kg of sow and kg swine live-weight at the barn gate (GOLINELLI hog barn).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	1.93; 3.69	Average pig breeding production in Europe – Agri-footprint database[5][6]; Average national mix for swine live-weight production in Italy – World Food LCA database[7]
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	8.55E-8; 1.32E-7	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	0.0544; 0.0453	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.00617; 0.015	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	2.51E-7; 2.22E-7	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	5.36E-8; 3.08E-9	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database

[5] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 1 - Methodology and basic principles. Gouda, the Netherlands.

[6] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 2 - Description of data. Gouda, the Netherlands.

[7] Bengoa, X., Chappuis, C., Guignard, C., Liernur, A., Kounina, A., Papadimitriou, C., Rossi, V. & Bayart, J-B. (2019). World Food LCA Database Documentation. Version 3.5, November 2019. Quantis, Lausanne, Switzerland.

Table 4. The Environmental Impact Category Indicators (EICIs) per kg of sow and kg swine live-weight at the barn gate (GOLINELLI hog barn) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	7.51E-10; 5.97E-10	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.0311; 0.0367	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	0.00046; 0.000277	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	0.00917; 0.0219	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	0.135; 0.165	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	168.0; 15.6	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Land Use	Soil quality index (SQI)	Pt	174.0; 175.0	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Water use	m3 water eq. deprived (WU)	m3 depriv.	0.98; 5.71	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database

Table 4. The Environmental Impact Category Indicators (EICIs) per kg of sow and kg swine live-weight at the barn gate (GOLINELLI hog barn) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	11.0; 20.5	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	7.18E-6; 2.55E-6	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database

The EICI values of the same average pig breeding production system in Europe focusing on the weaned piglets' live-weight output (i.e. per kg of piglet live-weight output), as modelled in the Agri-footprint database are shown in Table 5. In Table 5, the EICI values per kg of swine live-weight produced on an average swine farming system in Italy, as modelled in the World Food LCA database are still presented. For both systems, cradle-to-farm-gate system boundaries were applied. These EICI values could be considered as reference environmental performance metrics for the GOLINELLI-Nursery Barn system.

Table 5. The Environmental Impact Category Indicators (EICIs) per kg of piglet and kg swine live-weight at the barn gate (GOLINELLI nursery barn).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	3.84; 3.69	Average pig breeding production in Europe – Agri-footprint database[8,9]; Average national mix for swine live-weight production in Italy – World Food LCA database[10]

[8] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 1 - Methodology and basic principles. Gouda, the Netherlands.

[9] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 2 - Description of data. Gouda, the Netherlands.

[10] Bengoa, X., Chappuis, C., Guignard, C., Liernur, A., Kounina, A., Papadimitriou, C., Rossi, V. & Bayart, J-B. (2019). World Food LCA Database Documentation. Version 3.5, November 2019. Quantis, Lausanne, Switzerland.

Table 5. The Environmental Impact Category Indicators (EICIs) per kg of piglet and kg swine live-weight at the barn gate (GOLINELLI nursery barn) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	1.7E-7; 1.32E-7	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	0.108; 0.0453	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.0123; 0.015	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	5.0E-7; 2.22E-7	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	1.07E-7; 3.08E-9	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	1.49E-9; 5.97E-10	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database

Table 5. The Environmental Impact Category Indicators (EICIs) per kg of piglet and kg swine live-weight at the barn gate (GOLINELLI nursery barn) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.0619; 0.0367	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	0.000915; 0.000277	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	0.0183; 0.0219	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	0.269; 0.165	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	335.0; 15.6	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Land Use	Soil quality index (SQI)	Pt	346.0; 175.0	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database

Table 5. The Environmental Impact Category Indicators (EICIs) per kg of piglet and kg swine live-weight at the barn gate (GOLINELLI nursery barn) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Water use	m3 water eq. deprived (WU)	m3 depriv.	1.95; 5.71	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	21.8; 20.5	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database
Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	1.43E-5; 2.55E-6	Average pig breeding production in Europe – Agri-footprint database; Average national mix for swine live-weight production in Italy – World Food LCA database

The EICI values of an average pig fattening production system in Belgium (i.e. per kg of finished pigs' live-weight output), as modelled in the Agri-footprint database are shown in Table 6. For this system, cradle-to-farm-gate system boundaries were applied. These EICI values could be considered as reference environmental performance metrics for the ILVO swine farming system.

Table 6. The Environmental Impact Category Indicators (EICIs) per kg of finished pig live-weight at the barn gate (ILVO experimental farm).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	3.12	Average pig fattening production in Belgium – Agri-footprint database[11, 12]

[11] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 1 - Methodology and basic principles. Gouda, the Netherlands.

[12] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 2 - Description of data. Gouda, the Netherlands.

Table 6. The Environmental Impact Category Indicators (EICIs) per kg of finished pig live-weight at the barn gate (ILVO experimental farm) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	1.2E-7	Average pig fattening production in Belgium – Agri-footprint database
Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	0.0754	Average pig fattening production in Belgium – Agri-footprint database
Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.00861	Average pig fattening production in Belgium – Agri-footprint database
Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	5.33E-7	Average pig fattening production in Belgium – Agri-footprint database
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	1.05E-7	Average pig fattening production in Belgium – Agri-footprint database
Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	1.23E-9	Average pig fattening production in Belgium – Agri-footprint database
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.0612	Average pig fattening production in Belgium – Agri-footprint database
Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	0.000836	Average pig fattening production in Belgium – Agri-footprint database
Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	0.02	Average pig fattening production in Belgium – Agri-footprint database

Table 6. The Environmental Impact Category Indicators (EICIs) per kg of finished pig live-weight at the barn gate (ILVO experimental farm) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	0.227	Average pig fattening production in Belgium – Agri-footprint database
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	323.0	Average pig fattening production in Belgium – Agri-footprint database
Land Use	Soil quality index (SQI)	Pt	304.0	Average pig fattening production in Belgium – Agri-footprint database
Water use	m3 water eq. deprived (WU)	m3 depriv.	0.438	Average pig fattening production in Belgium – Agri-footprint database
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	14.9	Average pig fattening production in Belgium – Agri-footprint database
Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	1.07E-5	Average pig fattening production in Belgium – Agri-footprint database

The EICI values of an average enriched cage egg production system in Europe (i.e. per kg of eggs output), as modelled in the Agri-footprint database are shown in Table 7. For this system, cradle-to-farm-gate system boundaries were applied. These EICI values could be considered as reference environmental performance metrics for the AUA laying hen farming system.

Table 7. The Environmental Impact Category Indicators (EICIs) per kg of egg at the barn gate (AUA experimental farm).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	2.42	Average enriched cage egg production in Europe – Agri-footprint database[13, 14]
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	1.13E-7	Average enriched cage egg production in Europe – Agri-footprint database
Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	0.0525	Average enriched cage egg production in Europe – Agri-footprint database
Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.00901	Average enriched cage egg production in Europe – Agri-footprint database
Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	5.96E-7	Average enriched cage egg production in Europe – Agri-footprint database
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	6.3E-8	Average enriched cage egg production in Europe – Agri-footprint database
Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	9.84E-10	Average enriched cage egg production in Europe – Agri-footprint database
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.0572	Average enriched cage egg production in Europe – Agri-footprint database

Table 7. The Environmental Impact Category Indicators (EICIs) per kg of egg at the barn gate (AUA experimental farm) (continued).

[13] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 1 - Methodology and basic principles. Gouda, the Netherlands.

[14] Blonk Agri-footprint BV. (2022). Agri-Footprint - Part 2 - Description of data. Gouda, the Netherlands.

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	0.000674	Average enriched cage egg production in Europe – Agri-footprint database
Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	0.0111	Average enriched cage egg production in Europe – Agri-footprint database
Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	0.256	Average enriched cage egg production in Europe – Agri-footprint database
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	355.0	Average enriched cage egg production in Europe – Agri-footprint database
Land Use	Soil quality index (SQI)	Pt	272.0	Average enriched cage egg production in Europe – Agri-footprint database
Water use	m3 water eq. deprived (WU)	m3 depriv.	2.04	Average enriched cage egg production in Europe – Agri-footprint database
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	12.2	Average enriched cage egg production in Europe – Agri-footprint database
Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	6.65E-6	Average enriched cage egg production in Europe – Agri-footprint database

The EICI values for the medium voltage electricity consumption mix in Germany (i.e. per kWh of electricity consumed), as modelled in the Ecoinvent database are shown in Table 8. For this system, cradle-to-consumer system boundaries were applied (market activity). These EICI values could be considered as reference environmental performance metrics for the electric boiler system at the LVAT dairy cattle farm.

Table 8. The Environmental Impact Category Indicators (EICIs) per kWh of medium voltage electricity consumed (LVAT dairy cattle farm – Electric boiler).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	0.117	Electricity consumption mix in Germany – Ecoinvent database[15]
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	1.21E-9	Electricity consumption mix in Germany – Ecoinvent database
Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	0.00678	Electricity consumption mix in Germany – Ecoinvent database
Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.000178	Electricity consumption mix in Germany – Ecoinvent database
Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	1.02E-9	Electricity consumption mix in Germany – Ecoinvent database
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	7.13E-10	Electricity consumption mix in Germany – Ecoinvent database
Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	1.98E-10	Electricity consumption mix in Germany – Ecoinvent database
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.000239	Electricity consumption mix in Germany – Ecoinvent database

Table 8. The Environmental Impact Category Indicators (EICIs) per kWh of medium voltage electricity consumed (LVAT dairy cattle farm – Electric boiler) (continued).

[15] Ecoinvent (2024). Ecoinvent v3.10. Available at: https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/9369/documentation

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	1.68E-5	Electricity consumption mix in Germany – Ecoinvent database
Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	4.76E-5	Electricity consumption mix in Germany – Ecoinvent database
Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	0.000554	Electricity consumption mix in Germany – Ecoinvent database
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	0.404	Electricity consumption mix in Germany – Ecoinvent database
Land Use	Soil quality index (SQI)	Pt	0.306	Electricity consumption mix in Germany – Ecoinvent database
Water use	m3 water eq. deprived (WU)	m3 depriv.	0.00513	Electricity consumption mix in Germany – Ecoinvent database
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	1.84	Electricity consumption mix in Germany – Ecoinvent database
Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	2.24E-7	Electricity consumption mix in Germany – Ecoinvent database

The EICI values for the process of purification of biogas to biomethane in Switzerland (i.e. per m^3 of biomethane produced), as modelled in the Ecoinvent database are shown in Table 9. For this system, gate-to-gate system boundaries were applied. These EICI values could be considered as reference environmental performance metrics for the BioCNG unit system at the LVAT dairy cattle farm. Nevertheless, caution would be required due to the fact that in the values of Table 9, there is actually no environmental burden allocation to the main agricultural input (i.e. the input of the biogas plant substrates (e.g. dairy cattle manure)) of the process considered.

Table 9. The Environmental Impact Category Indicators (EICIs) per m3 of biomethane at the gate of the purification plant (LVAT dairy cattle farm – BioCNG unit).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	0.16	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database[16]
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	9.17E-10	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	0.0373	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.000214	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	2.96E-9	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	2.91E-9	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database

Table 9. The Environmental Impact Category Indicators (EICIs) per m3 of biomethane at the gate of the purification plant (LVAT dairy cattle farm – BioCNG unit) (continued).

[16] Ecoinvent (2024). Ecoinvent v3.10. Available at: https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/22468/documentation

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	3.98E-10	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.000418	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	2.23E-6	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	4.41E-5	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	0.000627	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	0.72	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Land Use	Soil quality index (SQI)	Pt	0.855	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database

Table 9. The Environmental Impact Category Indicators (EICIs) per m3 of biomethane at the gate of the purification plant (LVAT dairy cattle farm – BioCNG unit) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Water use	m3 water eq. deprived (WU)	m3 depriv.	0.0205	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	1.95	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database
Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	3.5E-6	Biogas purification to biomethane using membrane technique in Switzerland – Ecoinvent database

The EICI values for the process of tractor use for settling silage at a silage plat on a farm in France (i.e. per hr of diesel tractor use), as modelled in the Agribalyse database are shown in Table 10. For this system, the production, repair, and maintenance of all machines, fuel consumption and combustion, abrasion of tyres as well as shed or land used for parking the machines are included in the system boundaries. These EICI values could be considered as reference environmental performance metrics for the Tractor system at the LVAT dairy cattle farm.

Table 10. The Environmental Impact Category Indicators (EICIs) per hr of diesel tractor use (LVAT dairy cattle farm – Tractor).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Climate Change	Global Warming Potential 100 years (GWP100)	kg CO2-eq	46.4	Settling silage at a silage plat in France – Agribalyse database[17]

Table 10. The Environmental Impact Category Indicators (EICIs) per hr of diesel tractor use (LVAT dairy cattle farm – Tractor) (continued).

[17] Asselin-Balençon A., Broekema R., Teulon H., Gastaldi G., Houssier J., Moutia A., Rousseau, V., Wermeille A., Colomb V., Cornelus M., Ceccaldi M., Doucet M., Vasselon H., 2022. AGRIBALYSE 3 : la base de données française d'ICV sur l'Agriculture et l'Alimentation. Methodology for the food products. Initial publication Agribalyse 3.0 - 2020, update 3.1 - 2022 Ed. ADEME 2022.

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC11-eq	9.96E-6	Settling silage at a silage plat in France – Agribalyse database
Ionising radiation - human health	Ionizing Radiation Potential (IRP)	kg Bq U-235-eq	3.08	Settling silage at a silage plat in France – Agribalyse database
Photochemical ozone formation - human health	Photochemical ozone creation potential (POCP)	kg NMVOC-eq	0.551	Settling silage at a silage plat in France – Agribalyse database
Particulate matter	Disease incidence due to kg of PM2.5 emitted (DI)	disease inc.	9.96E-7	Settling silage at a silage plat in France – Agribalyse database
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUhnc)	CTUh	8.37E-7	Settling silage at a silage plat in France – Agribalyse database
Human toxicity, cancer	Comparative Toxic Unit for human (CTUhc)	CTUh	2.65E-8	Settling silage at a silage plat in France – Agribalyse database
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE-AC)	mol H+ eq	0.448	Settling silage at a silage plat in France – Agribalyse database
Eutrophication, freshwater	Phosphorus equivalents (PE)	kg P-eq	0.000331	Settling silage at a silage plat in France – Agribalyse database
Eutrophication, marine	Nitrogen equivalents (NE)	kg N-eq	0.183	Settling silage at a silage plat in France – Agribalyse database

Table 10. The Environmental Impact Category Indicators (EICIs) per hr of diesel tractor use (LVAT dairy cattle farm – Tractor) (continued).

ENVIRONMENTAL IMPACT CATEGORY	ENVIRONMENTAL IMPACT CATEGORY INDICATOR	UNIT	Indicator value	Reference
Eutrophication, terrestrial	Accumulated Exceedance (AE-TE)	mol N-eq	2.01	Settling silage at a silage plat in France – Agribalyse database
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	219.0	Settling silage at a silage plat in France – Agribalyse database
Land Use	Soil quality index (SQI)	Pt	113.0	Settling silage at a silage plat in France – Agribalyse database
Water use	m3 water eq. deprived (WU)	m3 depriv.	2.28	Settling silage at a silage plat in France – Agribalyse database
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	693	Settling silage at a silage plat in France – Agribalyse database
Resource use, minerals and metals	Abiotic resource depletion (ADP-ultimate reserve).	kg Sb-eq	0.000521	Settling silage at a silage plat in France – Agribalyse database

3 GOLINELLI COMPARATIVE LIFE CYCLE ASSESSMENT

3.1 Farm-level LCA models - GOLINELLI

3.1.1 Reference system - GOLINELLI

The commercial pig farm GOLINELLI is located in the Modena province, Italy (Figure 6a). The farm consists of a farrowing barn, a nursery barn, a gestation barn, and a hog barn with a gestation sector (Figure 6b). The buildings cover an area of about 3,800 m^2 and, except for the hog barn, they are made of precast reinforced concrete with thermal insulation.

(a) *(b)*

Figure 6. (a) General layout plan of the farm and (b) GOLINELLI farm building 12 (outside view).

The buildings of interest for the project are:

- Building 12 (B.12): a hog barn with an area of 663 m², capable of housing up to 500 sows, and
- Building 16 (B.16): a nursery barn covering 1,002 m², designed to accommodate up to 2,500 weaners, divided across 10 compartments.

In B.12 an LPG boiler of 115kW has been installed but has not operated regularly in the last few years. B.16's main corridor is heated by a 34 kW LPG boiler through finned tubes (water temperature of 70 °C), while each distinct room is heated by 5 thermal lamps of 1500 W each. Ventilation is achieved through an extraction fan and windows opening. Both buildings are made of precast reinforced concrete, and B.16 is insulated, while no thermal insulation is installed in B.12.

3.1.2 System after the interventions - GOLINELLI

To eliminate the fossil gas consumption of the LPG boiler, a 35 kW multi-source heat pump (HP) was installed in the nursery barn (B.16). Additionally, a PVT system[18] - consisting of 24 hybrid collectors - was installed to provide (i) thermal energy to a borehole thermal energy storage system (BTES), as well as (ii) electricity to the nursery barn. The BTES system consists of vertical boreholes of coaxial

[18] More details can be found in D1.4: "The developed PVT system designs dedicated for livestock farms".

type, at a depth of 10 m. It exploits both solar thermal energy and underground heat capacity by storing the excess heat from PVT, and it's connected to the HP to increase the Coefficient of Performance (COP).

The main intervention in B.12, the barn with no insulation, is a retrofit of the building envelope, by the replacement of the previous windows with a new opening system, equipped with an automation opening system suitable to minimise heat loss with proper air exchange.

A sensor-based smart control system was also installed for monitoring the indoor environment and outdoor conditions, as well as enabling communication between the systems. An overview of the total interventions is given in Figure 7 below:

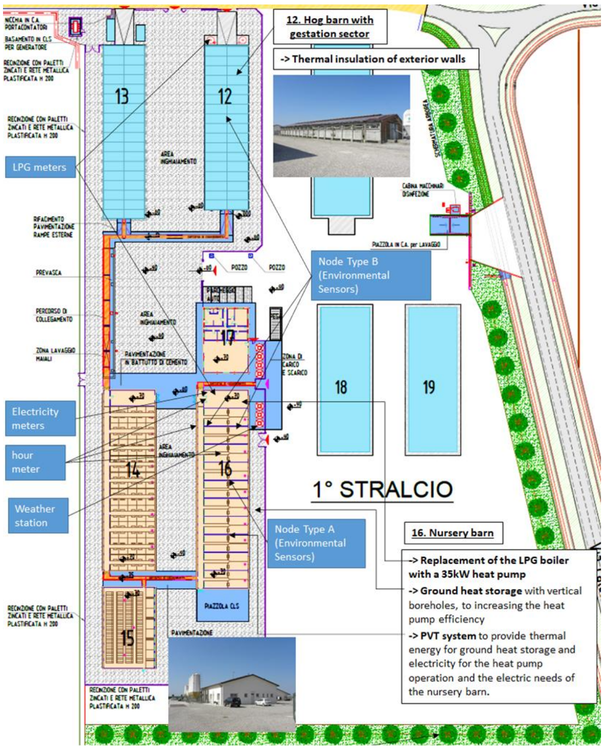

Figure 7. Overview of interventions in GOLINELLI farm.

For further details on the RES systems, please refer to deliverables D4.1: "Design of integrated systems in pilot farms", D4.2: "The installed pilot systems", D4.3: "Report with the test results obtained on energy and production performances of RES and energy efficiency solutions".

3.2 Farm-level LCA models - GOLINELLI

The annual product outputs from the hog barn (B.12) and the nursery barn (B.16) of the GOLINELLI farm, introduced into the SimaPro software, are shown in Table 11 below.

Table 11. Annual product outputs before and after the RES4LIVE interventions in the GOLINELLI pilot farm.

GOLINELLI - HOG BARN (B.12)	UNIT	REFERENCE	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS OPERATION)
Mature males production	kg live weight	1,050.00	
Sows culled	kg live weight	72,000.00	
GOLINELLI - NURSERY BARN (B.16)	**UNIT**	**REFERENCE**	**AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS OPERATION)**
Weaned piglets for sale	kg live weight	355,354.30	363,261.60
Weaned female piglets sent to the gestation barn	kg live weight	2,404.19	
Weaned male piglets sent to the hog barn	kg live weight	204.81	

The total, annual live weight of all animal categories is calculated based on the average live weight of the animals and their total number at the livestock housing gate, as provided by the farm managers. For animals in the hog barn, as well as the weaners sent to the gestation and hog barns, the same number of animals was used for both periods, since no notable differences were reported. Thus, no significant differences were expected.

The annual fuel and electricity consumption at the GOLINELLI pilot farm buildings, used to estimate the environmental burden before and after the RES4LIVE interventions, are presented in Table 12.

Table 12. Annual RES4LIVE inputs, fuel and electricity consumption & production before and after the RES4LIVE interventions in the GOLINELLI pilot farm.

HOG BARN (B.12)	UNIT	REFERENCE	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS' OPERATION)
Barn retrofit (New windows and opening system)	p	-	0.13[a]
Smart control system	p	-	0.10[b]

Table 5. Annual RES4LIVE inputs, fuel and electricity consumption & production before and after the RES4LIVE interventions in the GOLINELLI pilot farm (continued).

HOG BARN (B.12)	UNIT	REFERENCE	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS' OPERATION)
Barn retrofit (New windows and opening system)	p	-	0.13[a]
Smart control system	p	-	0.10[b]
LPG consumption (gas boiler)	kg	0.00	0.00
Total electricity consumption	kWh	107,772.16	156,541.20
Electricity consumed by the window opening system	kWh	-	481.8
Electricity consumed by the smart control system	kWh	-	164.25
NURSERY BARN (B.16)	**UNIT**	**REFERENCE**	**AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS' OPERATION)**
Heat pump	p	-	0.04[c]
PVT and solar station	p	-	0.04[c]
Borehole heat exchanger, for TES	p	-	0.16[d]
Smart control system	p	-	0.10[b]
LPG consumption (gas boiler)	kg	7,500.00	0.00
Total electricity consumption	kWh	406,595.40	412,420.80
Grid electricity used on farm	kWh	406,595.40	402,593.80

Table 5. Annual RES4LIVE inputs, fuel and electricity consumption & production before and after the RES4LIVE interventions in the GOLINELLI pilot farm (continued).

NURSERY BARN (B.16)	UNIT	REFERENCE	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS' OPERATION)
Electricity produced by the PVT system	kWh	-	9,827.00
Electricity used by the PVT system and accompanying equipment	kWh	-	228.00
Electricity consumed by the heat pump, including water pumps	kWh	-	7,963.00
Electricity consumed by the smart control system	kWh	-	114.98
[a] *1 piece of technology allocated to 30 years of lifetime* [b] *1 piece of technology allocated to 10 years of lifetime* [c] *1 piece of technology allocated to 25 years of lifetime* [d] *8 pieces of technology allocated to 50 years of lifetime*			

As mentioned, the LPG boiler in the hog barn (B.12) has not been used regularly in recent years due to higher outdoor temperatures. The reported increase in electricity consumption is attributed to the operation of newly installed window gear motors and a smart control system.

Regarding the nursery barn (B.16), despite the PVT electricity generation, total electricity consumption increased by approximately 5,825.4 kWh after the RES interventions. This increase is primarily due to the operation of the heat pump. However, the most notable impact of the interventions is the complete elimination of LPG use. The avoided emissions for eliminating its use in the nursery barn are presented in Table 13 below.

Table 13. Annual avoided farm-level emission flows from eliminating LPG use in the GOLINELLI nursery barn.

EMISSION	UNIT	EMISSION REDUCTION
CO_2 (Carbon dioxide)[a]	kg	22,148.1000
CH_4 (Methane)[a]	kg	1.7550

Table 6. Annual avoided farm-level emission flows from eliminating LPG use in the GOLINELLI nursery barn (continued).

EMISSION	UNIT	EMISSION REDUCTION
N_2O (Dinitrogen monoxide)[a]	kg	0.0351
NOx (Nitrogen oxides)[b]	kg	107.406
CO (Carbon monoxide)[b]	kg	32.643
NMVOC (Non-methane volatile organic compounds)[b]	kg	7.020
SOx (Sulfur oxides)[b]	kg	32.994
PM10 (Particulates, < 10 um)[b]	kg	7.371
PM2.5 (Particulates, < 2.5 um)[b]	kg	6.318
[a] *IPCC 2006* [b] *EMEP/EEA 2023*		

For detailed information on the Bill of Materials (BOM) for each unit comprising the integrated RES system installed at GOLINELLI, please refer to Section A.1, “GOLINELLI RES Systems BOM”.

3.3 Life cycle impact assessment: Findings and discussion - GOLINELLI

3.3.1 GOLINELLI Hog barn (B.12)

To understand the LCA results for the GOLINELLI hog barn, we will start by comparing the outcomes of the annual production cycle before the interventions (2020) (Reference system, RS) with the annual production after the interventions (year 2023-2024) (First year after interventions system, FYAIS), analysing the data at both the midpoint and endpoint levels.

Midpoint level assessment

Figure 8 presents the midpoint-level results for the two studied systems. The results suggest that the RS potentially outperforms the FYAIS in all EICIs. Particularly, an increase is observed in the ADP-

Fossil (23.23% and 22.07%, in minerals and metals, and fossil fuels, respectively). The CTU-hc increases by 19.13%. The same trend is also observed in the IRP (16.06% increase). This disadvantage of the FYAIS is primarily attributed to the use of more materials for the new technologies, as well as to the higher electricity consumption (operation of gear motors and smart control system). In terms of GWP100, the RS also performs better, mainly due to a lower use of electricity.

On the other hand, the two systems show comparable environmental performance in terms of the AE-TE (+0.26%), DI (0.37%), and AE-AC (0.46%).

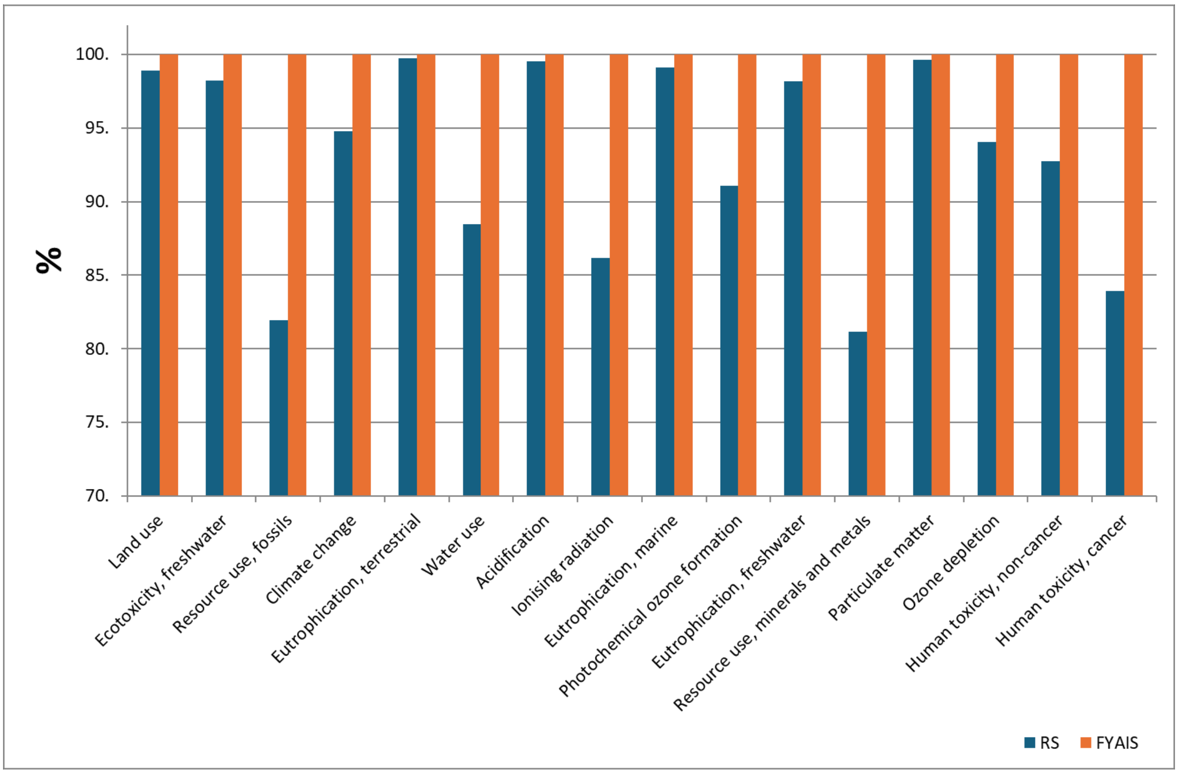

Figure 8. Midpoint environmental impact assessment of 1 kg of culled sows' live weight at the hog barn gate in the reference system (RS) vs the after-interventions system (FYAIS).

Table 14 presents the absolute difference in the EICIs complementary to the relative percentage difference provided in Figure 8.

Table 14. Difference in the EICIs expressed per kg of culled sows' live weight at the hog barn gate between the after interventions system (FYAIS) and the reference system (RS).

EIC/ EICI	UNIT (per kg of culled sows' live weight at the hog barn gate)	DIFFERENCE IN EICI
Climate change / GWP100	kg CO2 eq	0.247572273
Particulate matter / DI	disease inc.	8.00896E-09

Table 7. Difference in the EICIs expressed per kg of culled sows' live weight at the hog barn gate between the after interventions system (FYAIS) and the reference system (RS) (continued).

EIC/ EICI	UNIT (per kg of culled sows' live weight at the hog barn gate)	DIFFERENCE IN EICI
Water use / WU	m^3 depriv.	0.175261985
Resource use, fossils / ADP-fossil	MJ	3.875486117
Land use / SQI	Pt	1.6075219
Resource use, minerals and metals / ADP-ultimate reserve	kg Sb eq	3.27114E-06
Ozone depletion / ODP	kg CFC11 eq	5.66738E-09
Acidification / AE-AC	mol H+ eq	0.001460901
Ionising radiation / IRP	kBq U-235 eq	0.008088739
Photochemical ozone formation / POCP	kg NMVOC eq	0.000718473
Eutrophication, terrestrial / AE-TE	mol N eq	0.003619308
Eutrophication, marine / NE	kg N eq	0.000170268
Eutrophication, freshwater / PE	kg P eq	6.0932E-06
Human toxicity, cancer / CTU-hc	CTUh	6.73978E-10
Ecotoxicity, freshwater / CTUe	CTUe	0.864571397
Human toxicity, non-cancer / CTU-hnc	CTUh	3.0912E-09

Endpoint level assessment

Table 15 presents a comparison of the SES that can be attributed to the studied EICs between the RS and FYAIS. This comparison is also graphically presented in Figure 9. As expected from the midpoint analysis results, no individual categories showed reductions. The SES increased by 0.024 mPt after the interventions (a 1.89% increase), indicating a rise in the overall environmental burden. In both systems, acidification, particulate matter, and terrestrial eutrophication categories account for the largest share of the SES, with a minor relative decrease in the FYAIS. A slight relative increase is observed in climate change and resource use, minerals and metals categories. This can be explained by the higher electricity consumption of the FYAIS and the extraction of new materials for manufacturing the new systems. However, climate change, resource use (fossil fuels) and resource use (minerals and metals) are the EICs contributing more to the change in the total SES (Figure 9).

Table 15. Difference in the Single environmental score (SES) per kg culled sows' live weight at the hog barn gate between the after-interventions system (FYAIS) and the reference system (RS) for each EIC.

MIDPOINT EIC	UNIT (per kg of culled sows' live weight at the hog barn gate)	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Climate change	mPt	0.00163	29.16
Particulate matter	mPt	0.001205	5.09
Water use	mPt	0.00076	5.49
Resource use, fossils	mPt	0.006903	20.96
Land use	mPt	0.000258	0.66
Resource use, minerals and metals	mPt	0.00496	16.40
Ozone depletion	mPt	0.003882	0.03
Acidification	mPt	0.000293	6.89
Ionising radiation	mPt	0.000156	0.41
Photochemical ozone formation	mPt	0.0013	3.55
Eutrophication, terrestrial	mPt	0.000841	3.21
Eutrophication, marine	mPt	0.000442	1.09
Eutrophication, freshwater	mPt	0.000106	0.45

Table 8. Difference in the Single environmental score (SES) per kg culled sows' live weight at the hog barn gate between the after-interventions system (FYAIS) and the reference system (RS) for each EIC (continued).

MIDPOINT EIC	UNIT (per kg of culled sows' live weight at the hog barn gate)	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Human toxicity, cancer	mPt	0.000832	3.52
Ecotoxicity, freshwater	mPt	9.6E-05	1.24
Human toxicity, non-cancer	mPt	6.83E-06	1.87
Total	**mPt**	**0.02367**	**100**

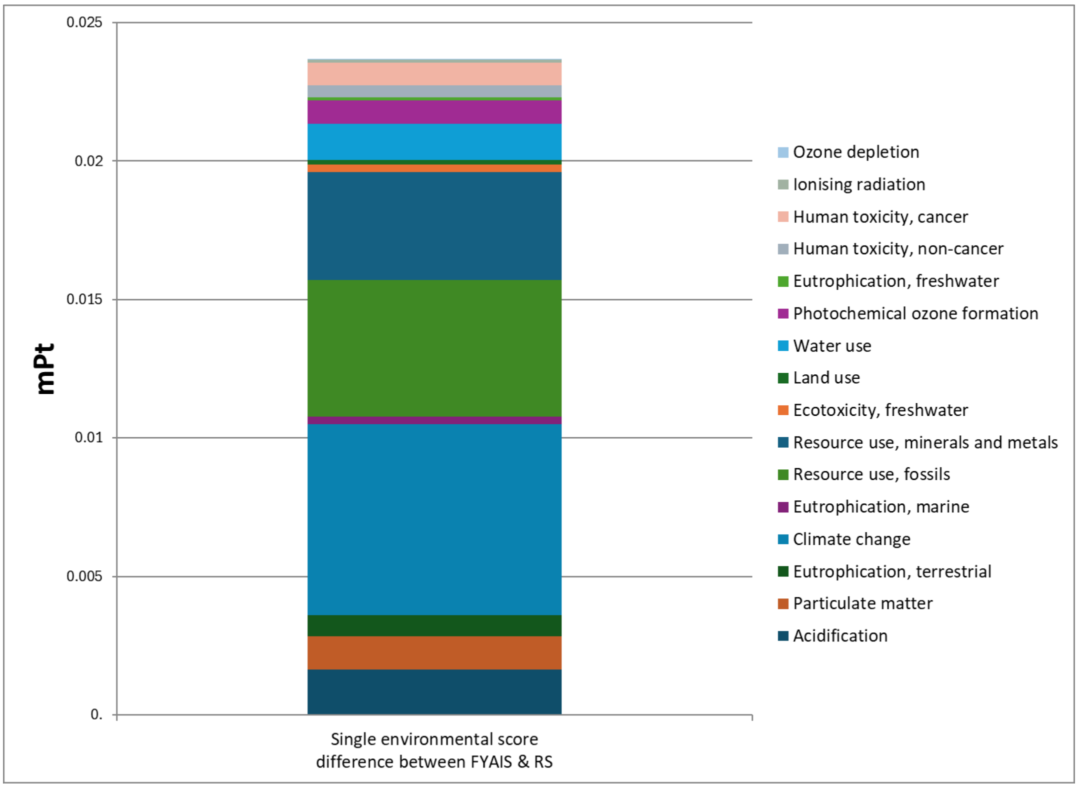

Figure 9. Graphical representation of the difference in the Single environmental score (SES) per kg of culled sows' live weight at the hog barn gate between the after-interventions system (FYAIS) and the reference system (RS).

In conclusion, while the interventions resulted in improved operational capabilities, a higher environmental impact is estimated after the first year of their operation. However, this may change in the following years if higher thermal losses are observed in the hog barn building. In addition, improving the internal climate conditions in the hog barn could result in an improvement in the sows' and boars' welfare and productivity, positively affecting the preparation of the farrowing process of the sows. Although this cannot be considered as a direct effect on the quantity of the product output from the hog barn (i.e., sows' and boars' live weight), there could be a direct effect on the quality of the sow and boar meat. There could also be a positive effect on the number of piglets born alive and healthy, potentially increasing the product output from the nursery barn and improving the environmental performance per kg of weaned piglets.

3.3.1 GOLINELLI Nursery barn (B.16)

Following the LCA results for the GOLINELLI nursery barn, the performance outcomes of the RS and FYAIS systems during the same period are compared at both midpoint and endpoint levels.

Midpoint level assessment

Figure 10 shows the midpoint-level results of the two studied systems. In this case, the results suggest that the FYAIS potentially outperforms the RS across all EICIs. Notably, there is a 6.04% reduction in the GWP100, alongside an important decrease in the ADP-fossil (13.39%) and POCP (14.89%). This advantage of the FYAIS is primarily due to the elimination of LPG use in the existing boiler, which was replaced by the integrated RES system (PVT/BTES/HP), with no notable increase in grid electricity consumption. Additionally, the 9,827.00 kWh of renewable electricity produced by the PVT system contributes to this improvement.

Other EICIs, such as WU and SQI, show potential decreases of 3.21% and 2.38%, respectively. This is attributed to the increase in the number of weaned piglets for sale, from 355,354.30 kg to 363,261.60 kg of live weight (+2.23%), indicating lower feed and water needs per kilogram of live weight. The smallest decrease is observed in the ADP-ultimate-reserve (0.72%), primarily due to the material inputs required for the manufacturing of the RES systems.

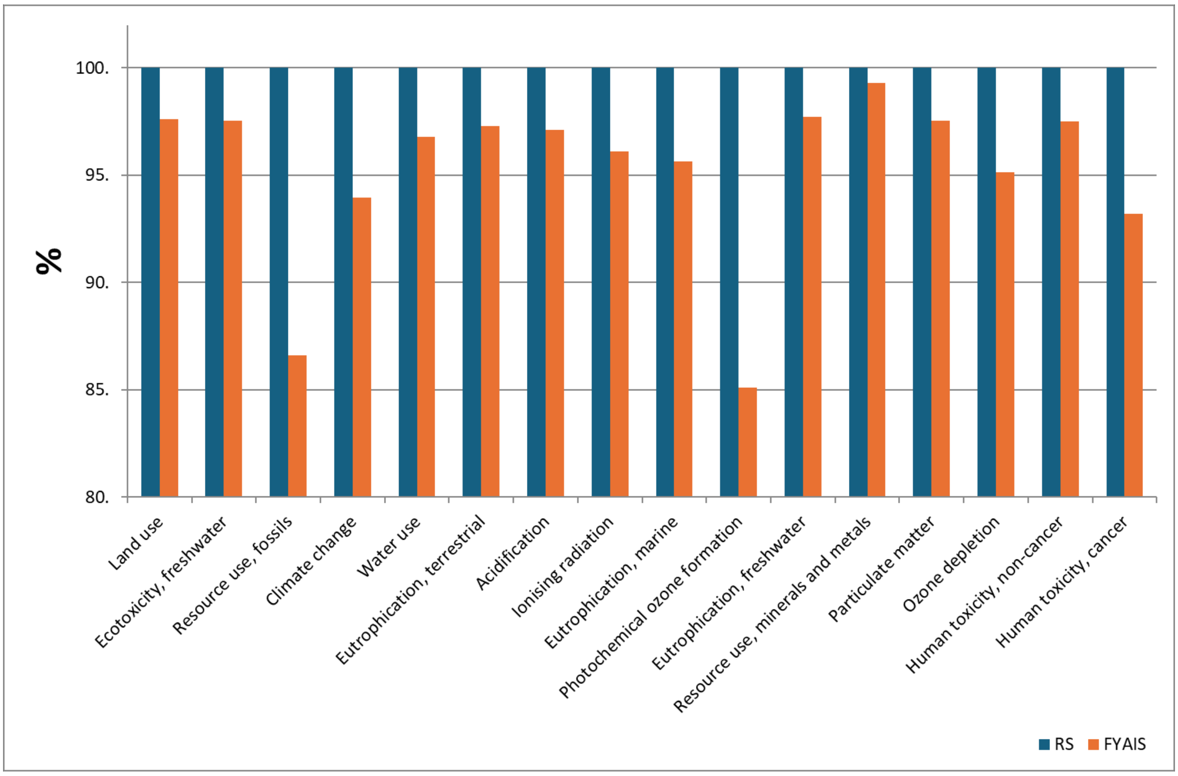

Figure 10. Midpoint environmental impact assessment of 1 kg of weaned piglets' live weight at the nursery barn gate in the reference system (RS) vs the after-interventions system (FYAIS).

Table 16 presents the absolute differences in the EICIs complementary to the relative percentage difference provided in Figure 10.

Table 16. Difference in EICIs per kg of weaned piglets' live weight at the nursery barn gate between the after-interventions system (FYAIS) and the reference system (RS).

EIC / EICI	UNIT (per kg of weaned piglets' live weight at the nursery barn gate)	DIFFERENCE IN EICI
Climate change / GWP100	kg CO2 eq	-0.14622225
Particulate matter / DI	disease inc.	-1.1008E-08
Water use / WU	m^3 depriv.	-0.02802376
Resource use, fossils / ADP-fossil	MJ	-1.63443452
Land use / SQI	Pt	-1.41155219

Table 9. Difference in EICIs per kg of weaned piglets' live weight at the nursery barn gate between the after-interventions system (FYAIS) and the reference system (RS) (continued).

EIC / EICI	UNIT (per kg of weaned piglets' live weight at the nursery barn gate)	DIFFERENCE IN EICI
Resource use, minerals and metals / ADP-ultimate reserve	kg Sb eq	-6.1797E-08
Ozone depletion / ODP	kg CFC11 eq	-2.3764E-09
Acidification / AE-AC	mol H+ eq	-0.00189486
Ionising radiation / IRP	kBq U-235 eq	-0.00111989
Photochemical ozone formation / POCP	kg NMVOC eq	-0.00065487
Eutrophication, terrestrial / AE-TE	mol N eq	-0.00760114
Eutrophication, marine / NE	kg N eq	-0.00027738
Eutrophication, freshwater / PE	kg P eq	-3.5821E-06
Human toxicity, cancer / CTU-hc	CTUh	-1.3695E-10
Ecotoxicity, freshwater / CTUe	CTUe	-0.54631313
Human toxicity, non-cancer	CTUh	-5.1355E-10

Endpoint level assessment

Figure 11 and Table 17 present a comparison of the SES that could be attributed to the studied EICs between the RS and FYAIS. The total SES potentially decreased by 13.65 µPt per kg of weaned piglets after the interventions (-4.06%), indicating a reduction in the overall environmental burden.

In both systems, acidification, particulate matter, climate change, and terrestrial eutrophication EICs account for the largest share of the systems' SESs. In the FYAIS, the relative importance of climate change and fossil fuel resource use decreases, while acidification potential and particulate matter emissions show a slight increase.

These results can be attributed, on one hand, to the elimination of LPG use, the modest increase in grid electricity consumption alongside the production of renewable energy, and on the other hand, the reduced feed and water needs per kilogram of live weight.

Table 17. Difference in the Single environmental score (SES) per kg weaned piglets' live weight at the nursery barn gate between the after-interventions system (FYAIS) and the reference system (RS) for each EIC.

EIC	UNIT (per kg weaned piglets' live weight at the nursery barn)	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Climate change	µPt	-0.073401124	29.88
Particulate matter	µPt	-0.184940821	12.14
Water use	µPt	-0.169073007	1.52
Resource use, fossils	µPt	-0.062419312	15.33
Land use	µPt	-0.420080339	1.29
Resource use, minerals and metals	µPt	-1.595442155	0.54
Ozone depletion	µPt	-0.766113227	0.22
Acidification	µPt	-0.013294833	15.49
Ionising radiation	µPt	-2.114127784	0.10
Photochemical ozone formation	µPt	-0.002864482	5.61
Eutrophication, terrestrial	µPt	-0.073333157	11.69
Eutrophication, marine	µPt	-0.136763261	3.08
Eutrophication, freshwater	µPt	-2.091939093	0.46
Human toxicity, cancer	µPt	-0.207941616	1.24

Table 10. Difference in the Single environmental score (SES) per kg weaned piglets' live weight at the nursery barn gate between the after interventions system (FYAIS) and the reference system (RS) for each EIC (continued).

EIC	UNIT (per kg weaned piglets' live weight at the nursery barn)	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Ecotoxicity, freshwater	µPt	-1.656586234	1.35
Human toxicity, non-cancer	µPt	-4.077064441	0.54
Total	**µPt**	**-13.6454**	**100**

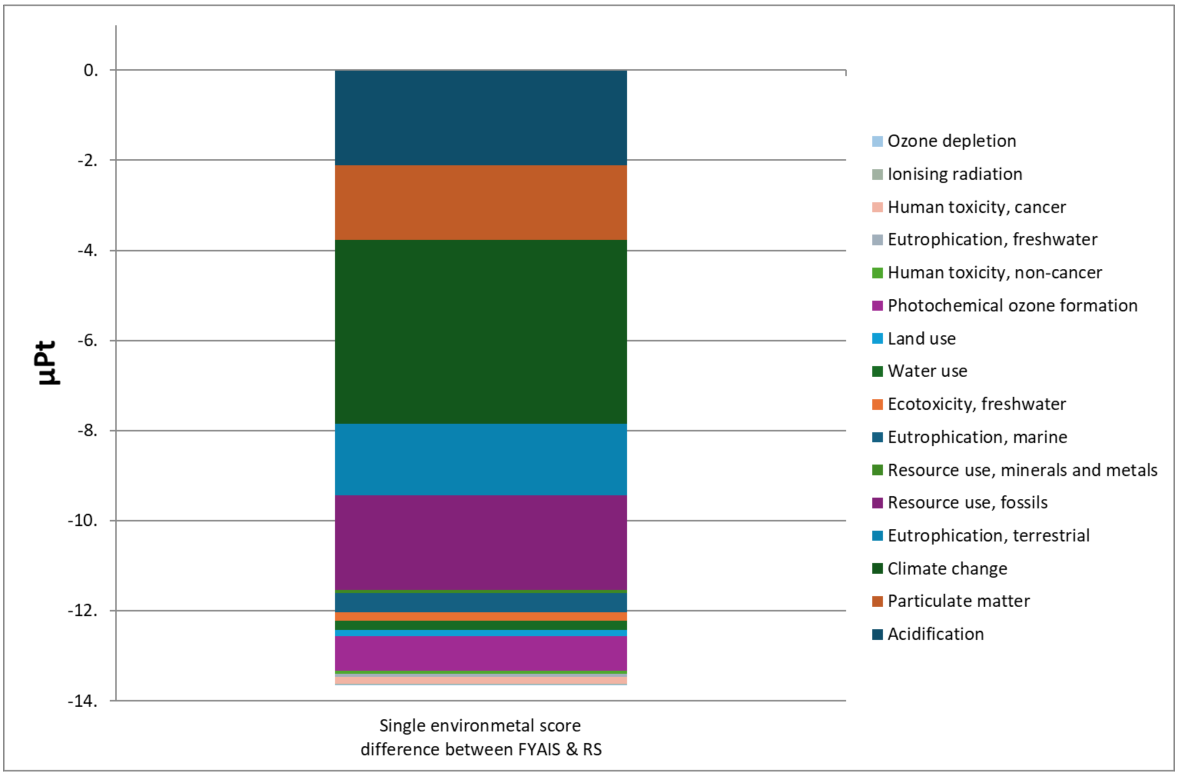

Figure 11. Graphical representation of the difference in the Single environmental score (SES) per kg of weaned piglets' live weight at the nursery barn gate between the after-interventions system (FYAIS) and the reference system (RS).

Contribution of RES4LIVE technology inputs

Table 18 presents the contribution of the four RES technologies installed in the GOLINELLI nursery barn to the total Environmental Impact Category Indicators (EICIs) per kilogram of weaned piglet live weight at the barn gate. The introduction of these new systems contributes approximately 0.21% (~0.68 μPt) to the total FYAIS SES. Specifically, the PVT system accounts for 0.145% (0.042 μPt), the BTES for 0.013% (0.103 μPt), the HP for 0.032% (0.467 μPt), and the smart control system for 0.021% (0.069 μPt).

In terms of the total environmental impact of the FYAIS, the integrated RES system at the GOLINELLI nursery barn contributes only 0.025%, 0.015%, and 0.112% to the impact categories of climate change, fossil resource use, and minerals and metals use, respectively. These figures clearly illustrate the minimal environmental impact of manufacturing and installing the RES systems compared to the overall impact of producing 1 kg of weaned piglet live weight.

Table 18. Contribution (in %) of the four GOLINELLI nursery barn RES technologies to the total EICI values of the FYAIS.

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PVT AND SOLAR STATION (%)	BTES (%)	HEAT PUMP (%)	SMART CONTROL (%)	TOTAL (%)
Climate change (GWP100)	0.018636706	0.002694	0.00275739	0.001197186	0.025285
Particulate matter (DI)	0.006909473	0.001058	0.001185711	0.000375082	0.009529
Water use (WU)	0.003425949	0.000242	0.000258551	9.36427E-05	0.00402
Resource use, fossils (ADP-fossil)	0.010901712	0.001805	0.001642572	0.000716661	0.015066
Land use (SQI)	0.000308286	3.19E-05	5.70188E-05	2.33836E-05	0.000421
Resource use, minerals and metals (ADP-ultimate reserve)	0.073569151	0.003209	0.018341787	0.017083553	0.112203
Ozone depletion (ODP)	4.08788E-05	3.02E-06	0.000140615	2.4273E-06	0.000187
Acidification (AE-AC)	0.007539696	0.000639	0.001422622	0.000391222	0.009993
Ionising radiation (IRP)	0.000243336	1.74E-05	3.08384E-05	2.15286E-05	0.000313
Photochemical ozone formation (POCP)	0.00359465	0.00056	0.000563419	0.000235528	0.004954

able 11. Contribution (in %) of the four GOLINELLI nursery barn RES technologies to the total EICI values of the FYAIS (continued).

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PVT AND SOLAR STATION (%)	BTES (%)	HEAT PUMP (%)	SMART CONTROL (%)	TOTAL (%)
Eutrophication, terrestrial (AE-TE)	0.00186581	0.000279	0.00030734	0.000138367	0.00259
Eutrophication, marine (NE)	0.001140685	0.000176	0.000180563	8.68257E-05	0.001584
Eutrophication, freshwater (PE)	0.000867096	6.69E-05	0.000148422	0.000132547	0.001215
Human toxicity, cancer (CTU-hc)	0.005712188	0.001649	0.002596276	0.000192622	0.01015
Ecotoxicity, freshwater (CTUe)	0.003035419	0.000333	0.000747772	0.000393586	0.00451
Human toxicity, non-cancer CTU-hnc)	0.006888033	0.000369	0.001479449	0.000316704	0.009053
Total (%)	**0. 144679069**	**0. 013131771**	**0. 031860347**	**0. 021400865**	**0. 211072**

4 EV ILVO COMPARATIVE LIFE CYCLE ASSESSMENT

4.1 Farm-level LCA models – EV ILVO

4.1.1 Reference system – EV ILVO

The farm "Varkenscampus" (Figure 12) is managed by EV ILVO, UGENT, and HoGent for research and educational purposes alongside normal commercial production. It is a farrow-to-finish pig farm hosting at any moment 105 sows, 600 piglets, and 750 fattening pigs. The total building area is approximately 2,500 m² and contains mainly concrete and insulation with polypropylene panels dividing the compartments and partially slatted concrete floors above the manure pits.

Figure 12. The EV ILVO pig farm.

Heating was provided year-round by a 60 kW natural gas condensing boiler. The hot water produced is used for three main purposes: (i) sanitary warm water, (ii) floor heating, and (iii) air heating. For sanitary warm water and air heating, the temperature of the water should be around 70 °C while for floor heating, a temperature of 40 °C is desired, as this entails low-temperature heating. Heat is delivered through a multitude of delivery systems depending on the need and the stage of production:

1. New-born piglets (Farrowing compartment): Floor heating and electric heat lamps
2. Weaned piglet compartment: Floor heating and heating of incoming air. The incoming air is heated using tubes in the air inlet channel where hot water is running through.
3. Fattening compartment: Heating of incoming air during cold periods. The heating system used is the same as for the weaned piglets. A gas cannon running on diesel fuel is used additionally for the first weeks of a new batch, especially during winter.
4. Sows: No need for extra heating (cooling is not supplied at the moment).

Moreover, the natural gas boiler supplies heat to a number of radiators in the kitchen, office, shower, meeting room, and hallway, as well as warm water for sanitary purposes (mainly showers).

A minimum amount of ventilation is needed to maintain a good indoor barn climate. This is achieved by bringing fresh air into the barn and keeping the pen air clean of pollutants, such as CO_2, NH_3, H_2S, dust, and moisture. The ventilation is further increased if the room temperature goes above the setpoint, in order to slightly cool the room with the outside air.

4.1.2 System after the interventions – EV ILVO

The RES installations in ILVO include: (i) two heat pumps (high- and medium-temperature) equipped with a short-term heat storage tank, (ii) 24 Abora panels PVT system accompanied with a solar station[19], (iii) a smart control system for the RES systems and the ventilation in one fattening pig room, (iv) environmental sensors and energy meters.

The entire farm is considered the building of interest, since the heat pumps and PVT system will provide heat and power, respectively, to the entire facility. The smart control system will focus on specific compartments additionally (four fattening, two farrowing, and three weaning compartments), as these have the possibilities for separate heating control.

The interventions are given briefly in Figure 13 below. The overall outcome of the interventions described above is the 100% replacement of gas with renewable systems, with electricity generation on-site as surplus.

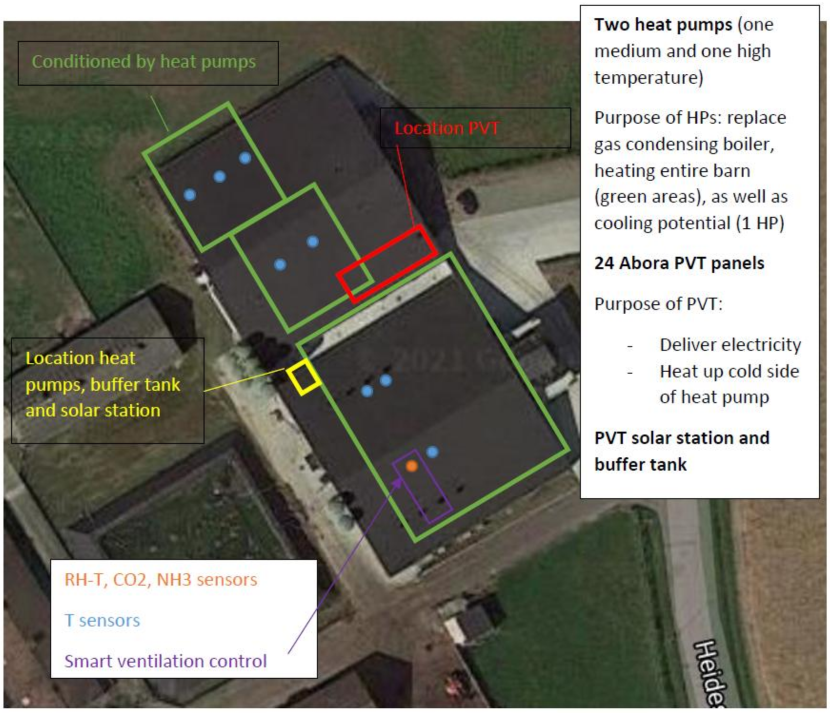

Figure 13. Overview of interventions at EV ILVO.

[19] More details can be found in D1.4: "The developed PVT system designs dedicated for livestock farms".

For further details on the RES systems, please refer to deliverables D4.1: “Design of integrated systems in pilot farms”, D4.2: “The installed pilot systems”, D4.3: “Report with the test results obtained on energy and production performances of RES and energy efficiency solutions”.

4.2 Farm-level LCA datasets – EV ILVO

The annual product outputs from the EV ILVO farm, introduced into the SimaPro software, are shown in Table 19 below.

Table 19. Annual product outputs before and after the RES4LIVE interventions in the EV ILVO pilot farm.

EV ILVO SWINE FARM	UNIT	REFERENCE YEAR	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS OPERATION)
Finished pigs for sale	kg live weight	181,366.30	189,148.80
Weaned piglets for sale	kg live weight	40,086.20	48,311.68
Mature sows for sale	kg live weight	7,304.70	7,512.96
Mature boars for sale	kg live weight	486.98	804.96

It should be noted that, as in the case of GOLINELLI, the annual live-weight output of all animal categories is calculated based on the average live weight of the animals and their total number at the livestock housing gate, as reported by the farm managers. Between the two periods studied, there was an overall increase of approximately 6.73% in animal production. Finished pigs sold live-weight increased by 4.11%, while the sold live-weights of weaned piglets, sows, and boars showed increases of 17.03%, 2.77%, and 39.05%, respectively.

Although the energy consumed and produced by both conventional and renewable energy systems (RES) was recorded during the monitoring and testing period, some extrapolations were necessary to conduct a full-year environmental life cycle assessment (LCA). These extrapolations were required because the new systems could not operate for the entire period due to various factors, including the fine-tuning phase. At the EV ILVO farm, the higher noise levels from the heat pump operation required the installation of additional sound insulation. As a result, the natural gas boiler had to compensate for the heat pumps during this downtime. However, the performance analysis of the systems, conducted as part of Tasks 4.3 and 5.1, allowed us to confidently extrapolate the expected performance and demonstrate the environmental benefits of the RES4LIVE interventions.

The annual fuel and electricity consumption and production at the EV ILVO pilot farm, used to estimate the environmental burden before and after the RES4LIVE interventions, are presented in Table 20.

Table 20. Annual fuel and electricity consumption and production before and after the RES4LIVE interventions in the EV ILVO pilot farm.

EV ILVO SWINE FARM	UNIT	REFERENCE YEAR	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS OPERATION)
Heat pumps	p	-	0.04[a]
PVT and solar station	p	-	0.04[a]
Smart control system	p	-	0.10[b]
Natural gas consumption (gas boiler)	m^3	22,603.90	0.00
Diesel consumption	kg	769.44	1,027.00
Total electricity consumption	kWh	114,233.90	197,634.00
Grid electricity used on farm	kWh	114,233.90	190,684.00
Electricity produced by the PVT system	kWh	-	6,950.00
Electricity used by the PVT system and accompanying equipment	kWh	-	228.00
Electricity consumed by the heat pump, including water pumps	kWh	-	76,650.00
Electricity consumed by the smart control system	kWh	-	164.25

[a] 1 piece of technology allocated to 25 years of lifetime
[b] 1 piece of technology allocated to 10 years of lifetime

In terms of fuel and energy consumption, the most notable impact of the RES interventions is the elimination of natural gas use, as the gas boiler has been replaced by heat pumps. However, this results in an 83,400.1 kWh increase in electricity consumption to operate the rest of the systems. Additionally, due to the higher demand for warm air provided by the heat cannon in the farrowing barn, diesel consumption has increased by 25%. All the renewable electricity produced by the PVT system (6,950.00 kWh) is consumed by the farm.

The avoided emissions for eliminating its use in the nursery barn are presented in Table 21 below.

Table 21. Annual avoided farm-level emission flows from eliminating natural gas and increased diesel use in the ILVO farm.

EMISSION	UNIT	EMISSION REDUCTION
CO_2 (Carbon dioxide)[a]	kg	41,101.0306
CH_4 (Methane)[a]	kg	3.6499
N_2O (Dinitrogen monoxide)[a]	kg	0.0714
NOx (Nitrogen oxides)[b]	kg	53.403
CO (Carbon monoxide)[b]	kg	21.033
NMVOC (Non-methane volatile organic compounds)[b]	kg	16.891
SOx (Sulfur oxides)[b]	kg	127.63
PM10 (Particulates, < 10 um)[b]	kg	0.494
PM2.5 (Particulates, < 2.5 um)[b]	kg	0.505
[a] *IPCC 2006* [b] *EMEP/EEA 2023*		

For detailed information on the Bill of Materials (BOM) for each unit comprising the integrated RES system installed at ILVO, please refer to Section A.2, "ILVO RES Systems BOM".

4.3 Life cycle impact assessment: Findings and discussion – EV ILVO

The LCA results for the EV ILVO swine farm are presented next. More particularly, the performance outcomes of the RS (years 2020-2022) and FYAIS (2023-2024) are compared at both midpoint and endpoint levels.

Midpoint level assessment

Figure 14 shows the midpoint-level results from the comparative assessment of FYAIS and RS. In this case, the results suggest that the FYAIS potentially outperforms the RS in almost all EICIs. Particularly, there is a 17.47% reduction in the GWP100, the EICI connected with the highest weighting factor across the environmental impact categories. Furthermore, notable are the decreased values in EICIs such as the ODP (18.56%), ADP-fossil (17.22%), POCP (15.11%) and CTU-hc (15.08%). Other EICIs, such as WU and SQI, show potential decreases of 6.34% and 10.94%, respectively.

Although a higher use of electricity and diesel fuel was reported during FYAIS, it outperforms RS due to the elimination of natural gas use in the existing boiler, which was replaced by the use of the heat pump and the PVT system. Additionally, the overall increase in output products (11.19%) contributes to this improvement.

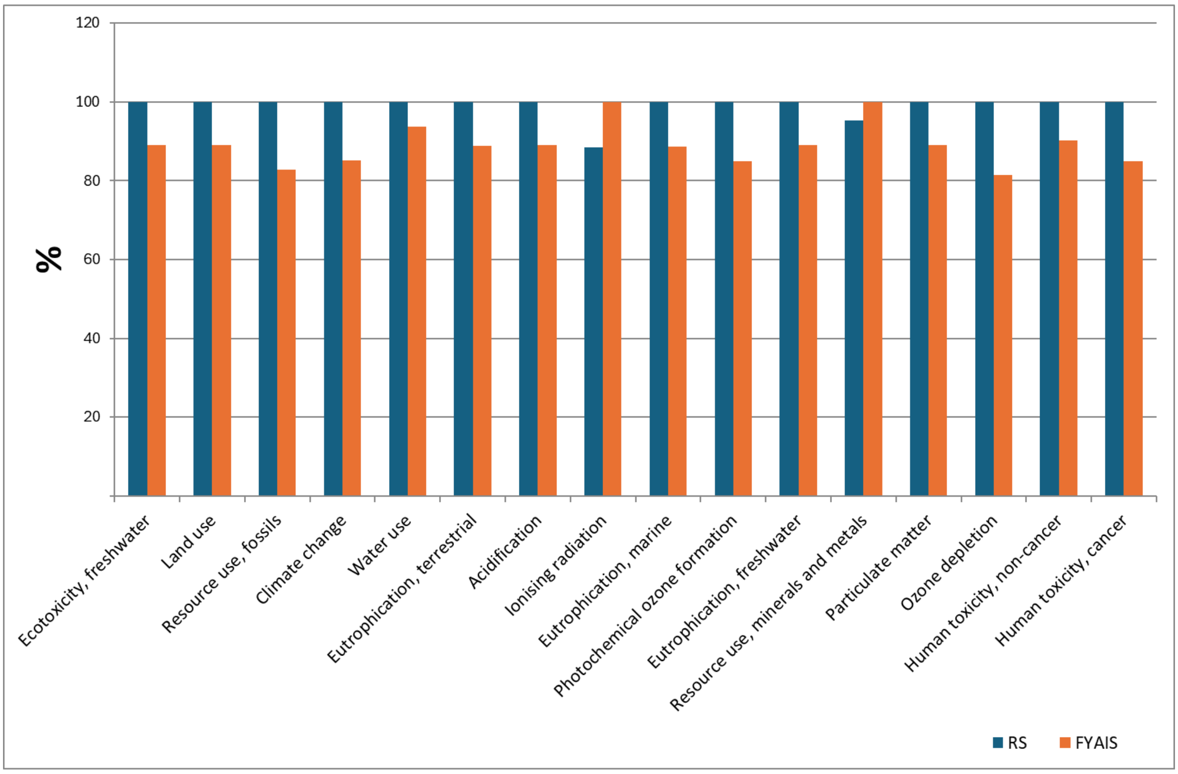

Figure 14. Midpoint environmental impact assessment of 1 kg of finished pigs' live weight at the farm gate in the reference system (RS) vs the after-interventions system (FYAIS).

The absolute values of the differences in the values of the EICIs are shown in addition to the relative percentage differences in Table 22.

Table 22. Difference in EICIs per kg of finished pigs' live weight at the farm gate between the after interventions system (FYAIS) and the reference system (RS).

EIC/ EICI	UNIT (per kg of finished pigs' live weight at the housing gate)	DIFFERENCE IN EICI
Climate change / GWP100	kg CO2 eq	-0.54446236
Particulate matter / DI	disease inc.	-8.003E-08
Water use / WU	m^3 depriv.	-0.03054158
Resource use, fossils / ADP-fossil	MJ	-3.55793969
Land use / SQI	Pt	-34.434449
Resource use, minerals and metals / ADP-ultimate reserve	kg Sb eq	5.81064E-07
Ozone depletion / ODP	kg CFC11 eq	-2.3046E-08
Acidification / AE-AC	mol H+ eq	-0.01104186
Ionising radiation / IRP	kBq U-235 eq	0.012418523
Photochemical ozone formation / POCP	kg NMVOC eq	-0.0011686
Eutrophication, terrestrial / AE-TE	mol N eq	-0.05015971
Eutrophication, marine / NE	kg N eq	-0.0025415
Eutrophication, freshwater / PE	kg P eq	-9.2451E-05
Human toxicity, cancer / CTU-hc	CTUh	-3.0608E-10
Ecotoxicity, freshwater / CTUe	CTUe	-35.4999002
Human toxicity, non-cancer	CTUh	-1.0731E-08

Endpoint level assessment

Figure 15 and Table 23 compare the single score results for the studied environmental impact categories between the RS and FYAIS. The total environmental impact decreased by 78.14 µPt after the interventions (-11.53%), indicating a significant reduction in the overall environmental burden in the FYAIS.

Despite the increase in SES for certain impact categories, the same EICs account for the majority of the relative importance in both systems. Acidification, particulate matter, freshwater ecotoxicity, and climate change represent the largest shares of the systems' SESs. In the FYAIS, as expected, the relative importance of climate change and fossil fuel resource use decreases, while acidification and particulate matter EICs show a marginal increase. Moreover, the differences in SES values for climate change, acidification, particulate matter, freshwater ecotoxicity and terrestrial eutrophication seem to be mostly responsible for the total difference in the SES value between FYAIS and RF.

These outcomes can be explained by the elimination of natural gas use, the modest increase in grid electricity consumption paired with renewable energy production, and the increased product output with approximately the same feed and water input.

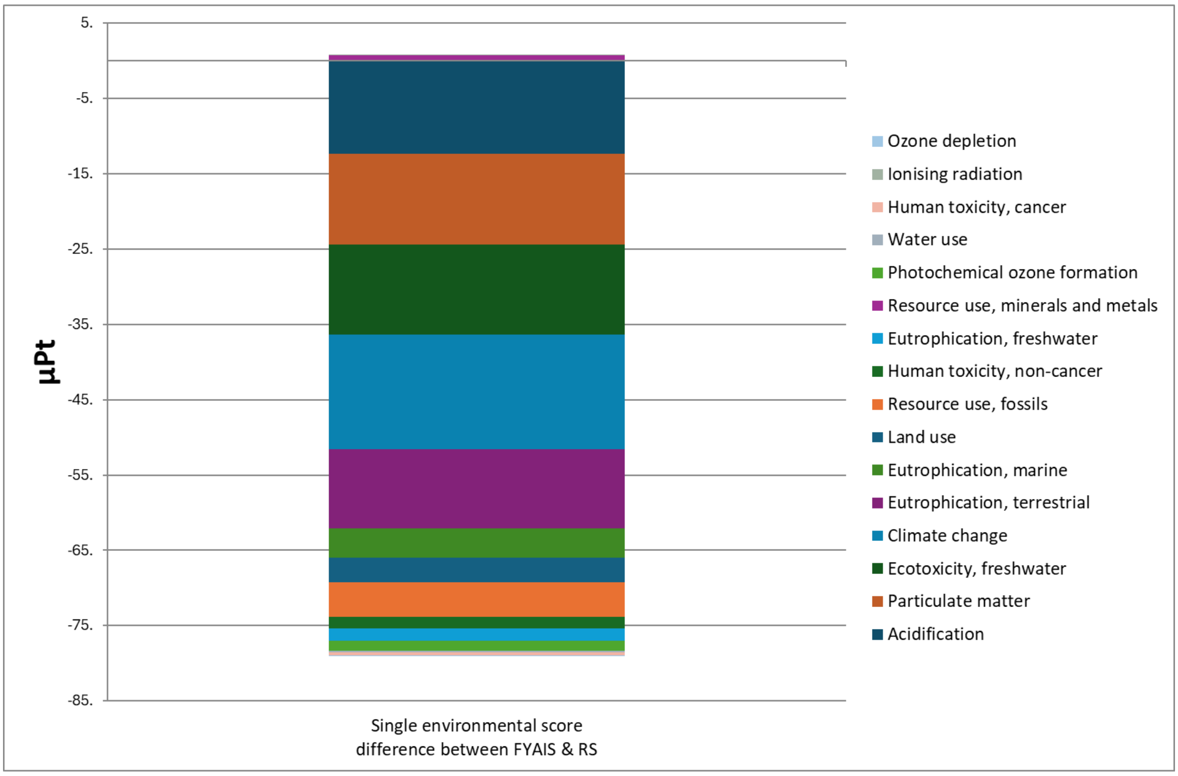

Figure 15. Difference in the Single environmental score (SES) kg of finished pigs' live weight at the farm gate between the after-interventions system (FYAIS) and the reference system (RS).

Table 23. Difference in the Single environmental score (SES) per kg finished pigs' live weight at the farm gate between the after interventions system (FYAIS) and the reference system (RS) for each EICI.

EIC	UNIT	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Climate change	µPt	-15.1811	19.43
Particulate matter	µPt	-12.0442	15.41
Water use	µPt	-0.22662	0.29
Resource use, fossils	µPt	-4.55386	5.83
Land use	µPt	-3.3363	4.27
Resource use, minerals and metals	µPt	0.689539	-0.88
Ozone depletion	µPt	-0.02778	0.035
Acidification	µPt	-12.3196	15.77
Ionising radiation	µPt	0.147427	-0.19
Photochemical ozone formation	µPt	-1.36711	1.75
Eutrophication, terrestrial	µPt	-10.5283	13.47
Eutrophication, marine	µPt	-3.84896	4.93
Eutrophication, freshwater	µPt	-1.61099	2.06
Human toxicity, cancer	µPt	-0.37788	0.48

Table 16. Difference in the Single environmental score (SES) per kg finished pigs' live weight at the farm gate between the after interventions system (FYAIS) and the reference system (RS) for each EICI (continued).

EIC	UNIT	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Ecotoxicity, freshwater	µPt	-12.0176	15.38
Human toxicity, non-cancer	µPt	-1.53375	1.96
Total	**µPt**	**-78.137**	**100**

Contribution of RES4LIVE technology inputs

Table 24 presents the contribution of the three RES technologies installed in the EV ILVO swine farm to the total Environmental Impact Category Indicators (EICIs) per kilogram of finished pig live weight at the farm gate. The introduction of these new systems contributes 0.29% (0.296 µPt) to the total FYAIS environmental impact. Specifically, the PVT system accounts for 0.222% (1.329 µPt), the HPs for 0.049%, and the smart control system for 0.018% (0.109 µPt).

In terms of the total environmental impact of the FYAIS, the integrated RES system at the EV ILVO farm contributes only 0.005% (0.006 kg $CO_{2\text{-eq}}$), 0.003% (0.077 MJ), and 0.042% (7.317E-07 kg Sb_{eq}) to the impact categories of climate change, use of fossil resources, as well as mineral and metals, respectively.

These figures clearly illustrate the minimal environmental impact of manufacturing and installing the RES systems compared to the overall impact of producing 1 kg of finished pig live weight.

Table 24. Contribution (in %) of the three EV ILVO farm RES technologies to the total EICI values of the FYAIS.

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PVT AND SOLAR STATION (%)	HEAT PUMP (%)	SMART CONTROL (%)	TOTAL (%)
Climate change (GWP100)	0.022	0.004476346	0.00103452	0.027476613
Particulate matter (DI)	0.0127	0.00195772	0.00032697	0.014953338

Table 17. Contribution (in %) of the three EV ILVO farm RES technologies to the total EICI values of the FYAIS (continued).

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PVT AND SOLAR STATION (%)	HEAT PUMP (%)	SMART CONTROL (%)	TOTAL (%)
Water use (WU)	0.0031	0.000398604	8.05124E-05	0.003618329
Resource use, fossils (ADP-fossils)	0.0132	0.002524711	0.00061787	0.016390454
Land use (SQI)	0.0005	8.96961E-05	2.05504E-05	0.000614233
Resource use, minerals and metals (ADP-ultimate reserve)	0.1025	0.027775165	0.014465344	0.144786206
Ozone depletion (ODP)	3E-05	0.000107248	2.03227E-06	0.000142353
Acidification (AE-AC)	0.0284	0.002413111	0.000349198	0.031165847
Ionising radiation (IRP)	0.0002	5.07209E-05	1.84654E-05	0.000309021
Photochemical ozone formation (POCP)	0.0093	0.000905503	0.000206393	0.010427148
Eutrophication, terrestrial (AE-TE)	0.0062	0.000508914	0.000120721	0.006815772
Eutrophication, marine (NE)	0.0032	0.000299216	7.68757E-05	0.003544008
Eutrophication, freshwater (PE)	0.0013	0.000226477	0.000112383	0.001649823
Human toxicity, cancer (CTU-hc)	0.0056	0.003987077	0.000169676	0.009723639

Table 17. Contribution (in %) of the three EV ILVO farm RES technologies to the total EICI values of the FYAIS (continued).

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PVT AND SOLAR STATION (%)	HEAT PUMP (%)	SMART CONTROL (%)	TOTAL (%)
Ecotoxicity, freshwater (CTUe)	0.005	0.001119937	0.000336725	0.006413357
Human toxicity, non-cancer (CTU-hnc)	0.0084	0.002470915	0.000308324	0.011183061
Total (%)	**0.2217**	**0.049311362**	**0.018246561**	**0.289213203**

5 AUA COMPARATIVE LIFE CYCLE ASSESSMENT

5.1 Farm-level LCA models - AUA

5.1.1 Reference system - AUA

The experimental poultry farm for egg production (Figure 10) has been established on the Agricultural University of Athens campus for more than 70 years. Its purpose is to support education provided to students with on-farm skills development, assist research contacted by the staff of the Animal Science Department, and provide the university and local community with fresh day-old eggs. The farm occupies an area of 90m^2, hosting approximately 400 animals. It is further divided into two separate equally sized poultry houses of 45 m² (15m x 3m); pullets' and a laying hens' house. Both pullets and hens are reared in a 3-tier colony cage production system. Hens are housed in enriched cages.

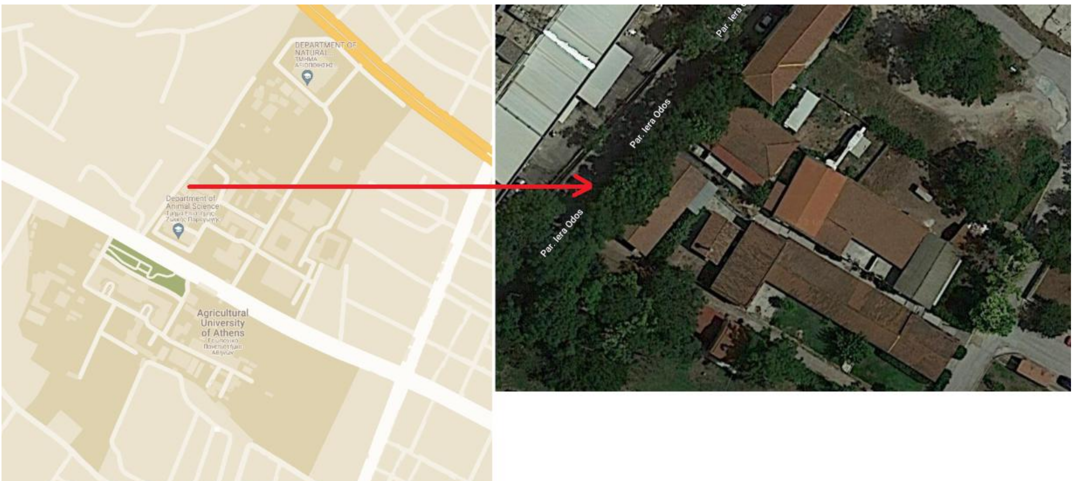

Figure 16. The AUA experimental poultry farm.

The poultry houses were of closed type with 0.57 m thick, rocky walls and poorly insulated, with polyurethane foam, and roofs with tiles. No cooling system was operated in either house.

1. <u>Pullets' house:</u> Winter and summer ventilation was applied with direct drive fans operated manually. For the first month of chicken growth, the house used to be heated by infrared heating lamps. Lighting was provided by 1m fluorescent lamps, and it was manually controlled by a timer.
2. <u>Laying hens' house:</u> Winter and summer ventilation was applied with direct drive fans operated manually. No heating or cooling system was installed before RES4LIVE, relying only on forced ventilation for removing the thermal loads during summer. Lighting was provided by 1m fluorescent lamps, and it was manually controlled by a timer.

5.1.1 System after the interventions - AUA

To enhance the thermal comfort of hens and broilers, a heat pump of PSYCTOTHERM with a capacity of 10 kW was installed. Moreover, to reduce the electricity consumption from the grid, standard PV panels of 8 kWp were installed on the rooftop of a nearby building, as well as inverter-driven motors of the ventilators. The smart control of PLEGMA was installed to manage the: (i) indoor environment for keeping the temperature and humidity within the thermal comfort zone, (ii) regulation of the ventilator fan speed, and (iii) PV power production for maximising self-consumption. The overall target was to make the building climate-neutral by replacing 100% of the whole electricity consumption. An overview of the interventions installed is given in Table 24.

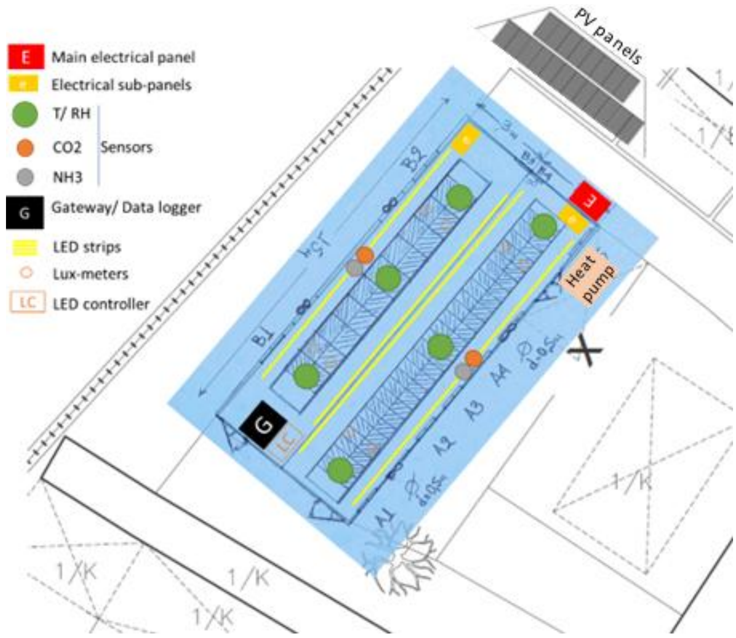

Figure 17. Overview of interventions in AUA farm.

For further details on the RES systems, please refer to deliverables D4.1: “Design of integrated systems in pilot farms”, D4.2: “The installed pilot systems”, D4.3: “Report with the test results obtained on energy and production performances of RES and energy efficiency solutions”.

5.2 Farm-level LCA datasets - AUA

The annual product outputs from the AUA farm, introduced into the SimaPro software, are shown in Table 25 below.

Table 25. Annual product outputs before and after the RES4LIVE interventions in the AUA pilot farm.

AUA FARM	UNIT	REFERENCE YEAR	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS OPERATION)
Laying Hens	heads	402	330
Mortality Rate	%	17.67	12.73
Total egg Production	eggs	70,786	78,129
Average production per animal	egg/hen/year	219	260

Table 25 compares the productivity of the AUA laying hen farm between the Reference Year and the period After Interventions, focusing on key metrics such as the number of hens, mortality rate, total egg production, and average production per hen per year. These metrics provide insights into how farm management and conditions changed over time and their impact on overall farm productivity.

In the Reference Year, the farm had a flock of 402 hens with a mortality rate of 17.67%, meaning that a significant portion of the flock was lost due to various factors, likely linked to suboptimal living conditions or health issues. After interventions, the number of hens decreased to 330 heads, but there was a noticeable improvement in hen welfare, as indicated by the reduction in the mortality rate to 12.73%. This suggests that the operation of the RES4LIVE technologies had a positive effect on the overall health and survival of the flock, despite the reduction in flock size.

Although the flock size decreased after interventions, the total number of eggs produced increased from 70,786 eggs in the Reference Year to 78,129 eggs after interventions. This increase in egg production, despite fewer hens, demonstrates a clear improvement in the productivity of laying hens. The interventions likely addressed issues related to housing and environmental conditions, resulting in healthier hens, experiencing improved housing and welfare conditions, that were able to produce more eggs over the year.

The average production per hen per year further highlights the productivity improvement. In the Reference Year, each hen produced an average of 219 eggs, while after the interventions, this figure rose to 260 eggs per hen per year—an increase of approximately 18.7%. This increase in individual hen productivity suggests that the farm's improvements allowed each hen to maximise its laying potential, mainly through better housing conditions.

Table 26. Annual electricity consumption parameters before and after the RES4LIVE interventions in the AUA pilot farm.

AUA FARM	REFERENCE YEAR	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS OPERATION)	AFTER INTERVENTIONS SCENARIO 1	AFTER INTERVENTIONS SCENARIO 2
Electricity produced by the PV system (kWh)	-	7,970.90	7,970.90	7,970.90
Renewable electricity consumed by the farm (kWh)	-	6,705.22	6,705.22	6,705.22
Electricity from the Grid consumed by the farm (kWh)	13,438.99	28,238.05	22,320.89	20,689.05
Electricity produced by the PV system but consumed elsewhere (kWh)	-	1,265.68	1,265.68	1,265.68
Electricity for lightning (kWh)	3,735.36	431.65	431.65	431.65
Electricity consumed by the heat pump (kWh)	**-**	**13,158.88**	**13,158.88**	**13,158.88**
Electricity consumed for ventilation (kWh)	**8,361.12**	**21,138.98**	**15,221.82**	**13,589.98**
Electricity consumed by the heat pump and ventilation systems (kWh)	8,361.12	3,4297.86	2,8380.70	2,6748.86
Electricity consumed by the smart control system (kWh)	-	118.26	118.26	118.26

Table 27. Annual electricity consumption parameters before and after the RES4LIVE interventions in the AUA pilot farm.

AUA FARM	REFERENCE YEAR	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS OPERATION)	AFTER INTERVENTIONS SCENARIO 1	AFTER INTERVENTIONS SCENARIO 2
Electricity consumed by infrared lamps, motors and personnel lighting (kWh)	1,342.51	95.50	95.50	95.50
Total electricity consumed by the farm (kWh)	**13,438.99**	**34,943.27**	**29,026.11**	**27,394.27**

Table 26 shows a detailed breakdown of electricity consumption for the AUA poultry house across the Reference Year, the After Interventions year, Scenario 1, and Scenario 2, all measured in kWh. It categorises the farm's electricity consumption into various sources and uses, including PV system production, grid electricity, and specific systems like heating, lighting, ventilation, and heat pumps.

In the Reference Year, the farm relied entirely on grid electricity, consuming 13,438.99 kWh. Major energy consumption sources included lighting (3,735.36 kWh) and ventilation systems (8,361.12 kWh). There was no use of renewable energy (e.g., PV system) during this year. By the After Interventions phase, there was a notable shift with the addition of the PV system, which produced 7,970.90 kWh of electricity, and the farm consumed 6,705.22 kWh of this renewable energy. Despite the introduction of the PV system, the farm's total energy consumption rose to 34,943.27 kWh, largely due to the installation of a heat pump (13,158.88 kWh) and an increase in ventilation energy consumption (21,138.98 kWh), indicating an overall increase in energy demand.

On top of the Reference Year and the After Renovations one, 2 additional scenarios are considered here to further explore the potential of the FYAIS Renovations system to improve its environmental performance for the RS Year. These 2 scenarios have been created based on the adjustment of an important parameter in the FYAIS Renovations system: the power size of the ventilation fan. Considering that the fan size used was probably overestimated to keep the ventilation system working more hours than necessary, leading to considerably high levels of electricity consumption, an optimisation strategy may require the use of smaller fans of lower power. Therefore, the use of a 1 hp (horsepower) fan (medium size) and of a 0.75 hp fan (small size) was considered in Scenario 1 (After Interventions Medium Sized Fan System, AIMSFS) and 2 (After Interventions Small Sized Fan System, AISSFS), respectively.

In Scenario 1, the total energy consumption decreased to 29,026.11 kWh, with grid electricity consumption dropping to 22,320.89 kWh. Although the heat pump energy usage remained constant (13,158.88 kWh), there was a notable reduction in ventilation energy demand to 15,221.82 kWh, reflecting more efficient energy usage. In Scenario 2, the total energy consumption further decreased to 27,394.27 kWh, with the lowest grid electricity consumption of 20,689.05 kWh. The ventilation system showed even more efficiency, using 13,589.98 kWh. Across both scenarios, the PV system consistently produced the same amount of energy (7,970.90 kWh), and there were no energy needs for heating using infrared lamps. Both scenarios demonstrate overall improvements in energy efficiency compared to the After Interventions phase. More details can be found in D5.1: "Technical assessment and validation of the numerical platform".

For detailed information on the Bill of Materials (BOM) for each unit comprising the integrated RES system installed at AUA, please refer to Section A.3, "AUA RES Systems BOM".

5.3 Life cycle impact assessment: Findings and discussion - AUA

5.3.1 Assessment based on measured data - AUA

To properly understand the LCA results associated with the AUA poultry house, we are going to first compare the results of a production cycle before the interventions (2020) (Reference system, RS) and one after them (2023) (First year after interventions system, FYAIS), by presenting and interpreting them at the midpoint and endpoint levels. After that, we will also introduce two new scenarios based on an adjustment of the size of the fans used in the second period, to assess the environmental impact of a more optimised ventilation system.

Midpoint level assessment

Starting with the midpoint level results, Figure 18 suggests that the RS potentially outperforms the FYAIS in most EICIs, particularly in terms of CTU-hc (with a 59.13% lower impact), ADP-ultimate reserve and ADP-fossil (with a 44% and 30.86% lower impact), and CTU-hnc (with a 30.38% lower impact). This advantage is largely attributed to the use of simpler materials in the more basic technologies used in the RS (which translates into the need for fewer heavy metals like lead and copper), lower electricity consumption because of the lower technology application in the RS and shorter transportation distances, which reduced the amount of diesel used.

In contrast, the FYAIS potentially shows better performance in EICIs such as CTUe (with a 9.46% lower impact), AE-TE (with a 5.41% lower impact), SQI (with a 10.27% improvement), and WU (with a 4.87% improvement). This is primarily the result of increased productivity after the renovations, as less feed is required per kilogram of egg produced, and overall lower water usage, leading to a more efficient system in these specific categories.

Regarding the GWP100, the RS also performs better, obtaining a 16.77% better result than the FYAIS. Despite this overall result, however, a more detailed analysis of the characterised results shows that while the RS performs 31.88% better in terms of CO2 eq emissions associated with the use of fossil fuels (mainly due to a considerably lower use of electricity), the FYAIS has a 15% better performance on biogenic CO2 eq emissions.

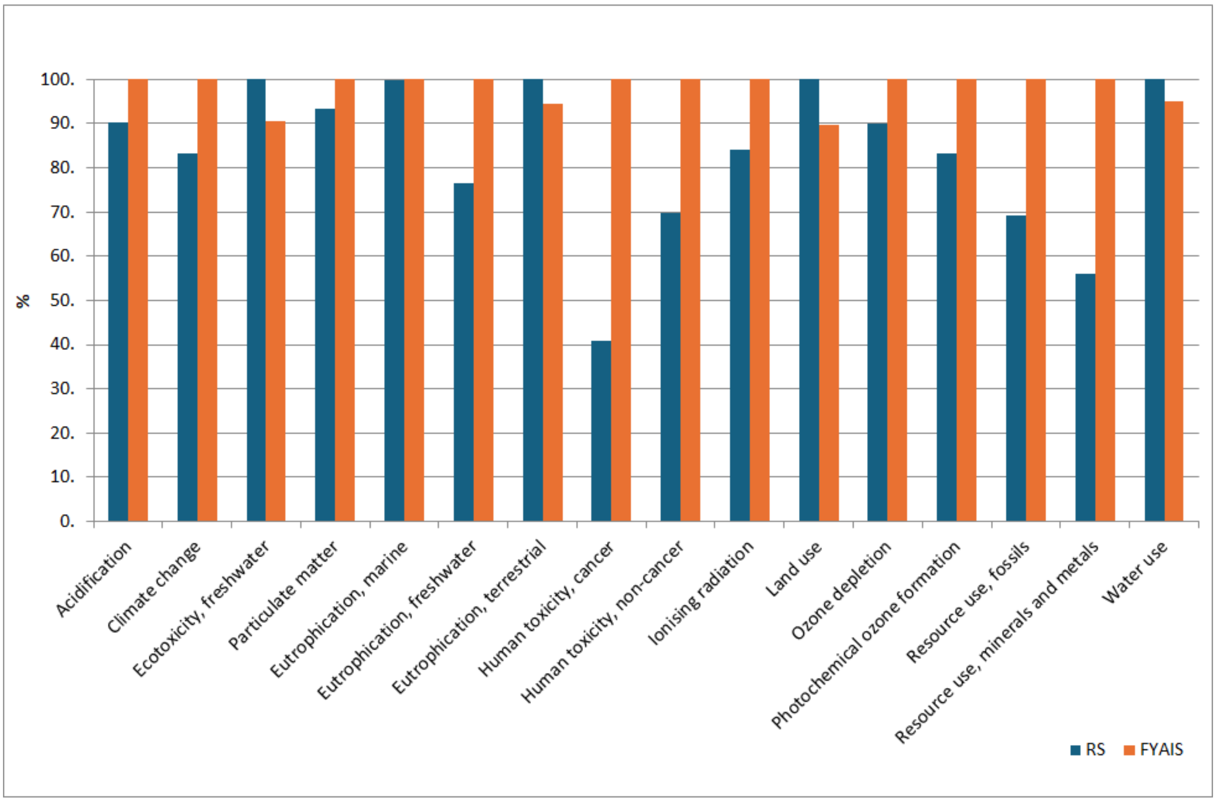

Figure 18. Midpoint environmental impact assessment of 1 kg of egg at the livestock housing gate in the reference system (RS) vs the after-interventions system (FYAIS).

The absolute differences in EICIs per kg of egg at the housing gate are provided in Table 28, in addition to the relevant % differences shown in Figure 18.

Table 28. Difference in midpoint environmental impact assessment of 1 kg of eggs at the livestock housing gate between the after-interventions system (FYAIS) and the reference system (RS), expressed in unit EICI/kg of eggs.

EIC/ EICI	UNIT (per kg of egg at the housing gate)	DIFFERENCE IN EICI
Climate change / GWP100	kg CO2 eq	0.636224688
Particulate matter / DI	disease inc.	2.0458E-08
Water use / WU	m^3 depriv.	-0.113485897

Table 20. Difference in midpoint environmental impact assessment of 1 kg of egg at the livestock housing gate between the after-interventions system (FYAIS) and the reference system (RS), expressed in unit EICI/kg of egg (continued).

EIC/ EICI	UNIT (per kg of egg at the housing gate)	DIFFERENCE IN EICI
Resource use, fossils / ADP-fossil	MJ	11.09286554
Land use / SQI	Pt	-19.9709206
Resource use, minerals and metals / ADP-ultimate reserve	kg Sb eq	1.06341E-05
Ozone depletion / ODP	kg CFC11 eq	1.7342E-08
Acidification / AE-AC	mol H+ eq	0.00186109
Ionising radiation / IRP	kBq U-235 eq	0.0141555
Photochemical ozone formation / POCP	kg NMVOC eq	0.002274835
Eutrophication, terrestrial / AE-TE	mol N eq	-0.003863544
Eutrophication, marine / NE	kg N eq	2.9973E-05
Eutrophication, freshwater / PE	kg P eq	0.000537245
Human toxicity, cancer / CTU-hc	CTUh	3.87773E-09
Ecotoxicity, freshwater / CTUe	CTUe	-20.276903
Human toxicity, non-cancer	CTUh	9.6506E-09

Endpoint level assessment

Figure 19 and Table 29 compare the SES for various EICs between the RS and FYAIS. The total SES has increased after interventions by 57.68 µPt, indicating an overall increase in environmental burden after the changes. Key areas of difference include climate change, where the impact increased by

17.74 µPt, use of fossil and mineral resources, which increased by 14.19 µPt and 12.62 µPt, respectively. These increases suggest that while the interventions may have improved operational efficiency in some areas, they also led to higher emissions related to higher energy consumption derived from the implementation of the new technologies.

Despite these increases, some categories showed improvements. For example, freshwater ecotoxicity decreased by 6.86 µPt, while land and water use also saw a reduction of 1.94 µPt and 0.84 µPt, respectively. These changes reflect better resource use efficiency, primarily because of the increase in feed conversion ratio following the interventions.

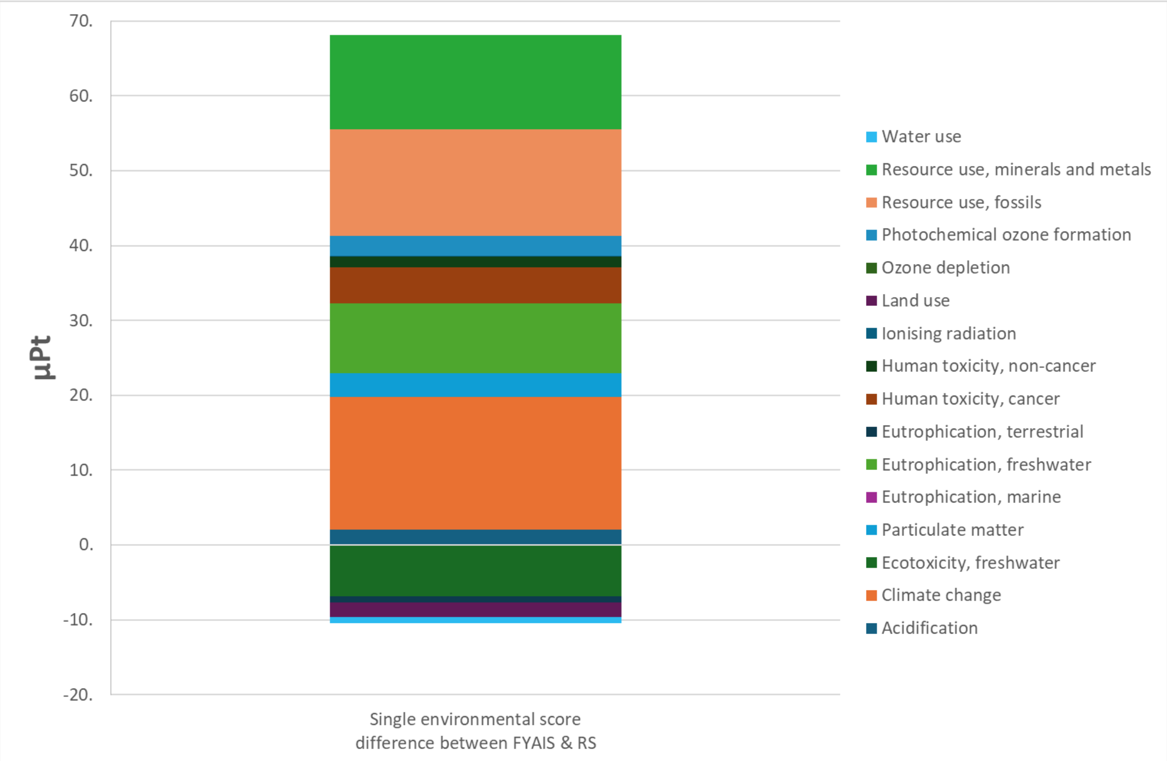

Figure 19. Difference in the Single environmental score (SES) per kg of eggs at the poultry house gate between the after-interventions system (FYAIS) and the reference system (RS).

Table 29. Difference in the Single environmental score (SES) per kg of eggs at the poultry house gate for the reference system (RS) vs the after-interventions system (FYAIS) for each EICI.

EIC	UNIT	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Climate change	µPt	17.740	30.76

Table 21. Difference in the Single environmental score (SES) per kg of eggs at the poultry house gate for the reference system (RS) vs the after-interventions system (FYAIS) for each EICI (continued).

EIC	UNIT	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Particulate matter	µPt	3.079	5.34
Water use	µPt	-0.842	-1.46
Resource use, fossils	µPt	14.198	24.62
Land use	µPt	-1.935	-3.35
Resource use, minerals and metals	µPt	12.619	21.88
Ozone depletion	µPt	0.021	0.04
Acidification	µPt	2.076	3.60
Ionising radiation	µPt	0.168	0.29
Photochemical ozone formation	µPt	2.661	4.61
Eutrophication, terrestrial	µPt	-0.811	-1.41
Eutrophication, marine	µPt	0.045	0.08
Eutrophication, freshwater	µPt	9.362	16.23

Table 21. Difference in the Single environmental score (SES) per kg of eggs at the poultry house gate for the reference system (RS) vs the after-interventions system (FYAIS) for each EICI (continued).

EIC	UNIT	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL SES DIFFERENCE (%)
Human toxicity, cancer	µPt	4.787	8.30
Ecotoxicity, freshwater	µPt	-6.864	-11.90
Human toxicity, non-cancer	µPt	1.379	2.39
Total	**µPt**	**57.68**	**100**

In conclusion, while the interventions have brought about improvements in some specific environmental categories, they have also resulted in higher impacts in critical areas like climate change and resource use. This suggests that further optimization, particularly in electricity consumption and material efficiency, may be necessary to mitigate these increases and achieve a more sustainable overall operation.

Contribution of RES4LIVE technology inputs

Table 30 focuses on presenting how the 4 RES4LIVE technologies' inputs (i.e. LED system, Heat Pump, Smart Control System and PV system) contribute to the total values of the EICIs per kg egg at the poultry housing gate. Taking GWP100 as an example, overall, of the 3.79 kg of CO_2eq per kg of egg generated in the FYAIS, the 4 technologies combined contributed only 5.64%, with the Smart control system having the lowest contribution with 0.17%, the LED System contributing 1.53%, and the PV system and the Heat pump being the highest contributors with 1.91% and 2.03% respectively. Therefore, although the FYAIS increases the GWP_{100} by 16.77% in comparison to the RS, the RES4LIVE technology inputs contribute only a very small portion to it, with higher electricity consumption being the main driver of CO_2eq emissions.

Table 30. Contribution (in %) of the four AUA poultry farm RES technologies to the total EICI values of the FYAIS.

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PV SYSTEM (%)	HEAT PUMP (%)	SMART CONTROL (%)	LED SYSTEM (%)	TOTAL (%)
Climate change (GWP100)	0.297562808	0.299517474	0.009888843	0.229713946	0.836683071

Table 22. Contribution (in %) of the four AUA poultry farm RES technologies to the total EICI values of the FYAIS (continued).

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PV SYSTEM (%)	HEAT PUMP (%)	SMART CONTROL (%)	LED SYSTEM (%)	TOTAL (%)
Particulate matter (DI)	0.102663485	0.121490961	0.003303312	0.078889554	0.306347313
Water use (WU)	0.061162498	0.023523303	0.000971211	0.01426413	0.099921142
Resource use, fossils (ADP-fossil)	0.17187079	0.16326656	0.005916297	0.12837544	0.469429088
Land use (SQI)	0.004092661	0.005599132	0.000197702	0.002316692	0.012206186
Resource use, minerals and metals (ADP-ultimate reserve)	0.768189983	0.730943214	0.125964904	0.780406559	2.40550466
Ozone depletion (ODP)	0.000790005	0.00148916	1.90175E-05	0.000162681	0.002460863
Acidification (AE-AC)	0.087842954	0.092372216	0.00358232	0.05946967	0.24326716
Ionising radiation (IRP)	0.011368531	0.01053107	0.000458821	0.008525571	0.030883993
Photochemical ozone formation (POCP)	0.052312356	0.046818772	0.002031127	0.035293035	0.13645529
Eutrophication, terrestrial (AE-TE)	0.026276583	0.02613787	0.001155626	0.021108399	0.074678478
Eutrophication, marine (NE)	0.01799658	0.017492411	0.000797513	0.014808142	0.051094645
Eutrophication, freshwater (PE)	0.111324356	0.102758332	0.007616482	0.086390529	0.3080897

Table 22. Contribution (in %) of the four AUA poultry farm RES technologies to the total EICI values of the FYAIS (continued).

ENVIRONMENTAL IMPACT CATEGORY INDICATOR (EICI)	PV SYSTEM (%)	HEAT PUMP (%)	SMART CONTROL (%)	LED SYSTEM (%)	TOTAL (%)
Human toxicity, cancer (CTU-hc)	0.084152526	0.281452757	0.001848898	0.022762924	0.390217105
Ecotoxicity, freshwater (CTUe)	0.039072563	0.047287577	0.003038116	0.024057985	0.113456241
Human toxicity, non-cancer (CTU-hnc)	0.068790892	0.068074061	0.003451863	0.019199289	0.159516105
Total (%)	**1.90546957**	**2.038754872**	**0.170242052**	**1.525744545**	**5.640211039**

5.3.2 Assessment of alternative scenarios - AUA

Midpoint level assessment

To further explore the potential of the FYAIS to improve its environmental performance with respect to the RS, 2 scenarios have been developed based on the adjustment of an important parameter in the FYAIS: the power size of the ventilation fan. Considering that the current fan size was probably overestimated to keep the ventilation system working more hours than necessary, leading to considerably high levels of electricity consumption, an optimisation strategy may require the use of fans of lower power. Therefore, the use of a 1 hp fan (medium size) and of a 0.75 hp fan (small size) was considered in Scenario 1 (After Interventions Medium Sized Fan System, AIMSFS) and 2 (After Interventions Small Sized Fan System, AISSFS), respectively.

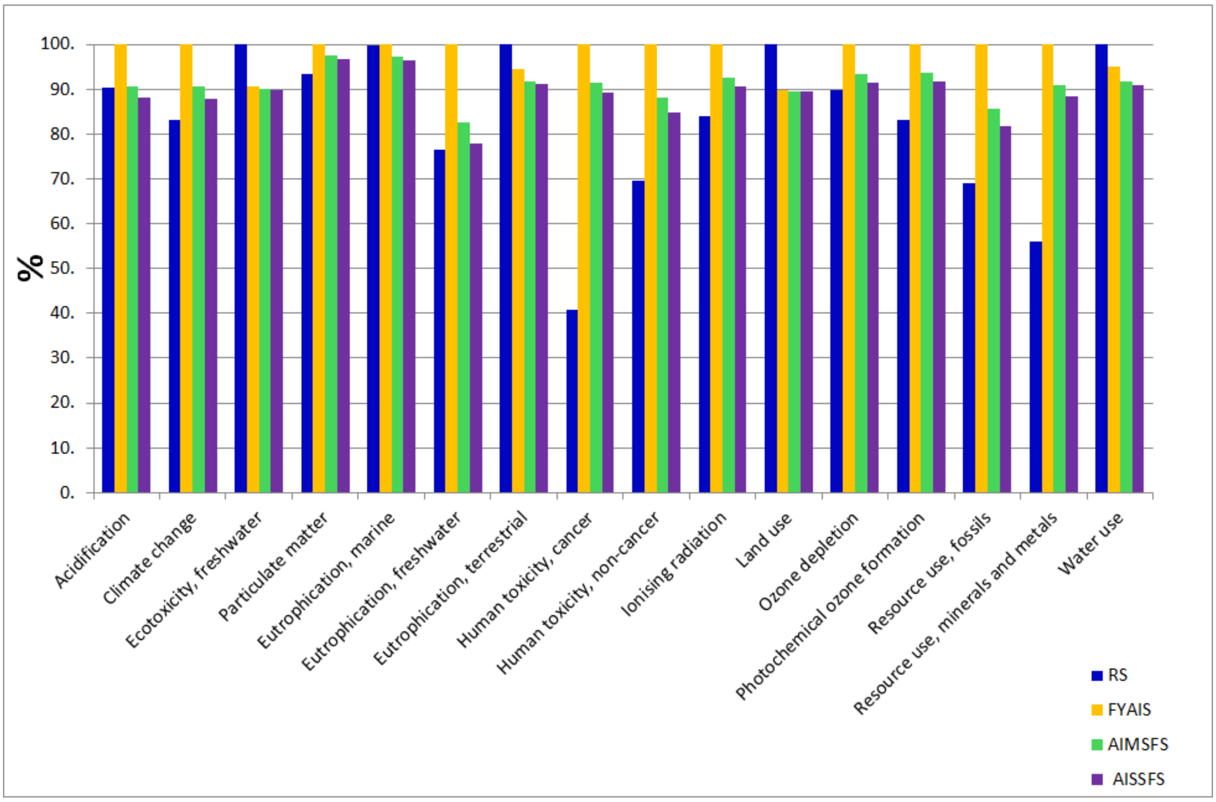

Figure 20. Midpoint level assessment per kg of egg at the poultry house gate of the systems RS, FYAIS, AIMSFS and AISSFS.

Figure 20 compares the same 16 impact categories across the various scenarios of interest. On top of the Reference Year and the After Renovations one presented in the previous section, 2 additional scenarios are considered here: Scenario 1 (representing the use of a medium size fan for ventilation, smaller than the one used in the After Renovations cycle) and Scenario 2 (representing the use of a small size fan instead). In this comparative analysis, both scenarios demonstrate notable improvements across several environmental impact categories from the After Renovations cycle.

According to the results, AIMSFS would perform better than the RS in 5 impact categories. In Freshwater Ecotoxicity, a 10% reduction is observed, indicating less contamination of water bodies with harmful chemicals, which is vital for maintaining aquatic biodiversity and water quality. Land use improves by 10.44%, suggesting a more efficient use of land resources, likely due to better management practices that minimise the space required for waste processing and disposal. In terms of water use, AIMSFS achieves an 8.2% improvement, meaning it utilises less water for the same processes compared to the RS, which is particularly important in regions like Greece where water scarcity is a concern. Eutrophication—the process by which water bodies receive excess nutrients that cause harmful algal blooms—also sees improvements: impacts on Terrestrial Eutrophication are reduced by 8.16%, while Marine Eutrophication by 2.52%, most likely due to the combined effect of better productivity obtained after renovations and the reduction in electricity consumption achieved by the smaller size fans for the ventilation system.

When it comes to AISSFS, it seems to demonstrate even stronger improvements, performing better than the RS in six impact categories. Impacts on Freshwater ecotoxicity are reduced by 10.14%, similar to AIMSFS, suggesting that both scenarios would be effective in reducing harmful pollutants from reaching water bodies. Land use improves slightly more than in AIMSFS, with a 10.49% improvement from the RS, due mainly to increased productivity and the most efficient use of feed, especially for the laying hens, which means less amount of feed required for a kg of egg.

A significant improvement is also seen in water use, where AISSFS achieves a 9.12% reduction from the RS values, highlighting its superior efficiency in conserving water. Eutrophication improvements are slightly better in AISSFS than in AIMSFS, with terrestrial eutrophication reduced by 8.91% and marine eutrophication by 2.31% from the RS, further preventing nutrient pollution in ecosystems. Additionally, AISSFS also shows a 2.40% improvement in acidification compared to the RS, mainly due to a combination of less electricity from the grid needed and higher productivity after the renovations allowing for a more efficient use of feed resources.

Endpoint level assessment

Table 31 and Figure **21** present the differences between the SES attributed to each EIC between the RS and (i) FYAIS, (ii) AIMSF, and (iii) AISSFS. Each impact category shows the environmental burden difference in micro-points (µPt), allowing for a comparison of the environmental performance across the different scenarios.

Table 31. Difference in the Single environmental score (SES) per kg of eggs at the poultry house gate between the RS and FYAIS, AIMSFS, and AISSFS for each EIC.

DAMAGE CATEGORY	UNIT	AIMSFS VS RS	AISSFS VS RS	AIMSFS VS FYAIS	AISSFS VS FYAIS
Climate change	µPt	7.71	4.95	-10.03	-12.79
Particulate matter	µPt	1.91	1.58	-1.17	-1.5
Water use	µPt	-1.42	-1.58	-0.58	-0.74
Resource use, fossils	µPt	7.64	5.84	-6.56	-8.36
Land use	µPt	-1.97	-1.98	-0.03	-0.04
Resource use, minerals and metals	µPt	10.03	9.32	-2.59	-3.3
Ozone depletion	µPt	0	0	-0.02	-0.02
Acidification	µPt	0.08	-0.47	-1.99	-2.54

Table 23. Difference in the Single environmental score (SES) per kg of eggs at the poultry house gate between the RS and FYAIS, AIMSFS, and AISSFS for each EIC (continued).

DAMAGE CATEGORY	UNIT	AIMSFS VS RS	AISSFS VS RS	AIMSFS VS FYAIS	AISSFS VS FYAIS
Ionising radiation	µPt	0.09	0.07	-0.08	-0.1
Photochemical ozone formation	µPt	1.64	1.36	-1.02	-1.3
Eutrophication, terrestrial	µPt	-1.22	-1.33	-0.41	-0.52
Eutrophication, marine	µPt	-0.35	-0.45	-0.39	-0.49
Eutrophication, freshwater	µPt	2.43	0.52	-6.94	-8.85
Human toxicity, cancer	µPt	4.1	3.91	-0.69	-0.88
Ecotoxicity, freshwater	µPt	-7.25	-7.36	-0.39	-0.5
Human toxicity, non-cancer	µPt	0.84	0.7	-0.54	-0.68
Total	**µPt**	**24.26**	**15.08**	**-33.43**	**-42.61**

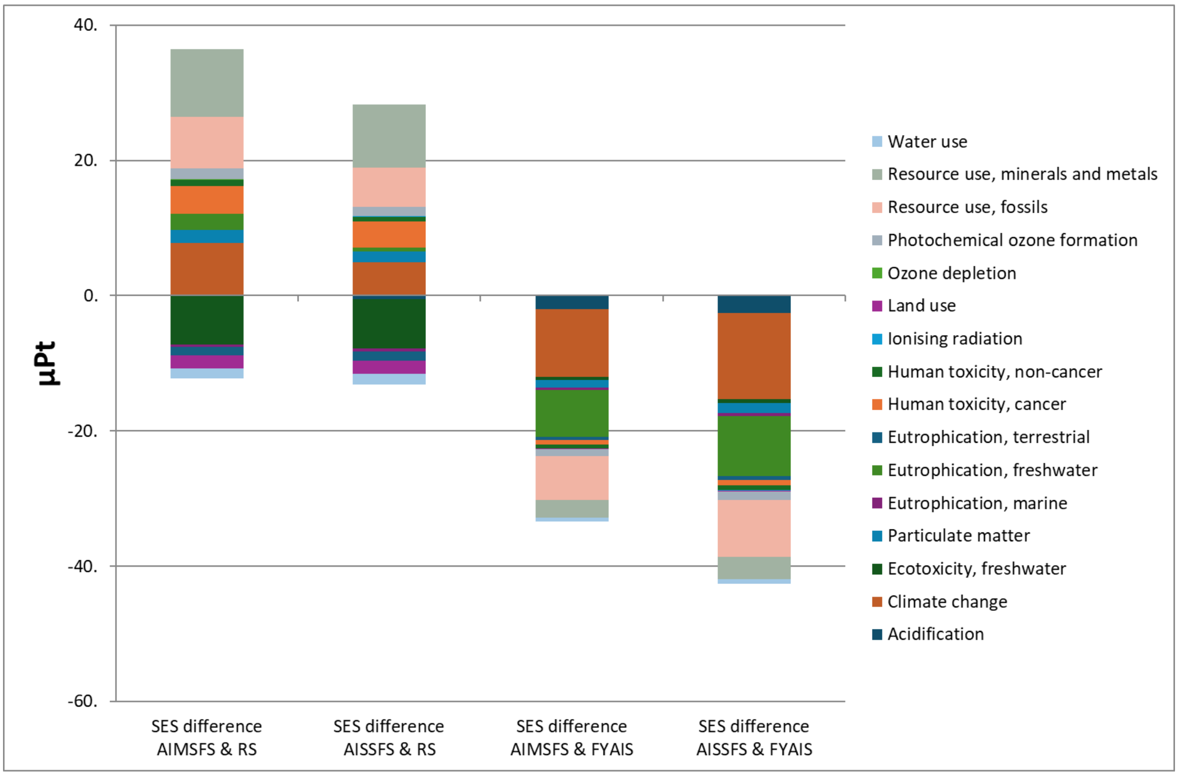

Figure 21. Single environmental score (SES) differences per kg of egg at the poultry house gate of the systems RS, FYAIS, AIMSFS and AISSFS.

Although the two additional scenarios (AIMSF and AISSFS) still show a slight increase in overall environmental impact compared to RS (by 24.26 µPt and 15.08 µPt, respectively), they demonstrate a reduction when compared to FYAIS, with decreases of 33.43 µPt and 42.61 µPt, respectively.

These improvements in relation to the FYAIS are reflected in several categories, such as Climate Change, where the impact decreases by 10.03 µPt in AIMSF and 12.79 µPt in AISSFS, Eutrophication (freshwater), which is reduced by 6.94 µPt and 8.85 µPt, and Resource Use (fossils, minerals and metals), which is reduced by 9.15 µPt and 11.66 µPt, respectively. These reductions reflect the reduced consumption of electricity obtained in the 2 scenarios thanks to the use of smaller size fans.

Moreover, other impact categories, such as Acidification and Particulate matter, also show improvements in AIMSF and AISSFS compared to FYAIS. For example, acidification potential drops by 1.99 µPt and 2.54 µPt in AIMSF and AISSFS, respectively. In the particulate matter category, the impact decreases by 1.17 µPt in AIMSF and 1.50 µPt in AISSFS. These findings indicate that the additional scenarios are more environmentally sustainable compared to the FYAIS, reflecting the impact that high levels of electricity consumption have across several environmental impact categories. At the same time, however, it is important to note that despite these reductions, the overall environmental impact in the two scenarios remains higher than in the Reference Year, suggesting that there is still room for further improvements.

6 LVAT COMPARATIVE LIFE CYCLE ASSESSMENT

6.1 Farm-level LCA models - LVAT

6.1.1 Reference system - LVAT

The Educational and Experimental Center for Animal Breeding and Husbandry (LVAT) is located in Groß Kreutz, in Brandenburg, Germany. The farm includes three barns for milk production with a total area of 3,950 m^2, with an overall number of 445 cows and calves. Barn A houses 150 cows in an area of approximately 2,240 m^2, Barn B houses 70 cows in an area of 630 m^2, and Barn C houses 140 cows in an area of 1,080 m^2 (Figure 22).

Figure 22. The LVAT farm.

The farm operates several fuel- and energy-consuming systems, but the following are involved in the RES4LIVE interventions (see the next section). An anaerobic manure digester is in operation, producing biogas for a CHP unit with a nominal power of 80 kWel and 96 kWth. The CHP unit generates electricity, which is sold to the national grid, while also providing hot water for various farm buildings, primarily the offices. Additionally, the farm is equipped with a diesel tractor and wheel loader for dairy management. An electric boiler, which receives water from the heat recovery system of the milk cooling unit, is also used to provide hot water for cleaning purposes in the barns.

6.1.2 System after the interventions - LVAT

Within RES4LIVE, a biogas upgrading unit was developed and demonstrated, as well as a retrofitted tractor for biomethane use. The installation of a PVT system was used for decentralised heat and electrical power generation. A smart management and control system was used to efficiently control heat and electricity consumption. Figure 23 shows an overview of the installations at LVAT. White boxes indicate existing systems and facilities, while green boxes indicate the RES4LIVE interventions.

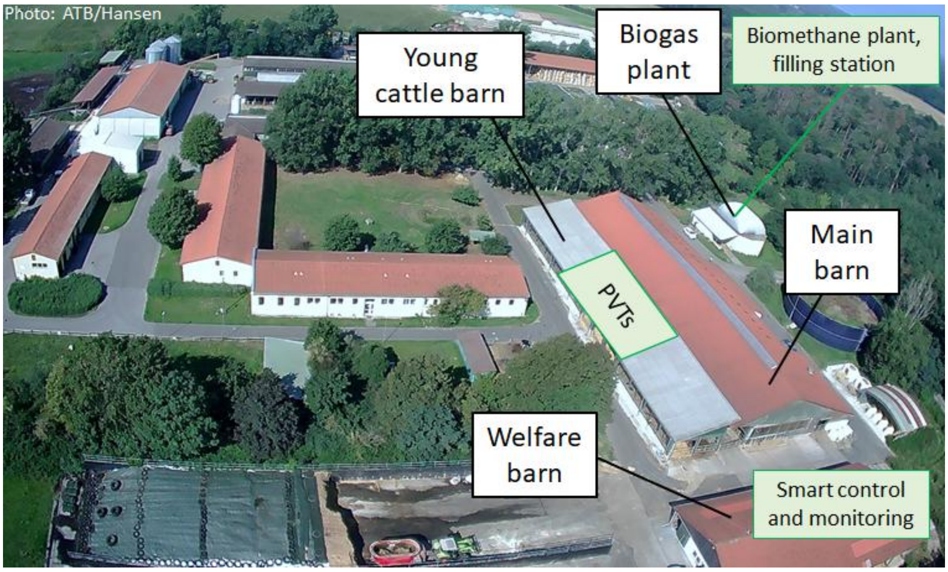

Figure 23. Overview of interventions in LVAT farm.

The BioCNG Unit

A small farm biogas plant with 80 kW_{el} electrical power has been in operation at the LVAT for many years (Figure 24).

Figure 24. The biomethane upgrading and fuelling station.

Since there were hardly any economically viable systems on such a small scale (10 Nm^3/h biomethane) on the market, a new technological setup with a hollow fibre membrane in the very low-pressure range (7-8 bar) and a hybrid compression was set up.

Since there were hardly any economically viable systems available on such a small scale, a new technological setup using a hollow fibre membrane in the very low-pressure range and hybrid compression was developed as part of the project. Additionally, a Bio-CNG farm filling station developed within this project features a simplified and compact design for the compression process. By integrating biogas-to-biomethane processing into the existing biogas CHP system, a single-stage (single membrane) process can be used for CH_4 concentration, instead of a multi-stage membrane process. As a result, there are no direct emissions at the biomethane stage, and the gas is further compressed for use at the Bio-CNG plant. More details can be found in D1.1: "Upgrading manure biogas to biomethane".

The Biomethane Tractor

A conversion kit for transforming the existing diesel farm tractor into a biomethane-fuelled tractor, optimising the trade-off between fuel economy, pollutant reduction, biogas variability, and conversion cost, was designed, produced, and operated on the LVAT farm (Figure 25).

A compact gas tank system was developed to carry enough fuel for approximately three hours of tractor operation at full load. The compressed gas storage system consists of multiple tanks, supplying biomethane to the engine. The selection and installation of the gas components adhered to ECE Regulation 110. More details can be found in D1.1: "The Adapted Farm Tractor Fueled by Biomethane".

Figure 25. The adapted biomethane tractor.

The PVT System

Since in LVAT, a high thermal demand, with high-temperature requirements, a novel concentrating PVT was deemed more efficient for temperatures higher than 50°C compared to flat-plate collectors (Figure 26). Due to budget constraints and a higher demand for thermal energy than electrical energy, it was decided to go with 24 collectors, where 20 will be PVT collectors and 4 will be thermal (the same collector but without the PV cells) giving a total aperture area of 45m^2. Having some collectors only deliver thermal energy gives the possibility to test and compare the performance of the collector with and without electrical output.

In the case of LVAT, the solar station was enclosed in a wooden structure, incorporating two heat storage units, insulation, and an additional control circuit to manage heat delivery from LVAT's heat recovery system. No inverter was installed in the solar station, as the Solarus CPVTs require specialised microinverters, which were placed on the roof. This design is specific to Solarus collectors.

Figure 26. The PVT system at LVAT.

For further details on the RES systems, please refer to deliverables D4.1: “Design of integrated systems in pilot farms”, D4.2: “The installed pilot systems”, D4.3: “Report with the test results obtained on energy and production performances of RES and energy efficiency solutions”.

6.2 Farm-level LCA datasets - LVAT

The annual product outputs, as well as fuel and energy consumption from the systems on the LVAT farm, introduced into the SimaPro software, are shown in Table 32 below.

Table 32. Annual outputs, fuel and energy consumption before and after the RES4LIVE interventions in the EV ILVO pilot farm.

CHP UNIT & BIOCNG UPGRADING UNIT AND FILLING STATION	UNIT	REFERENCE YEAR	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS' OPERATION)
Biomethane upgrading unit	p	-	0.667[c]
Biogas supplied to the CHP unit	m^3	160,329.67	118,697.48
Ignition oil used for CHP operation	lit	13,258.30	9,847.14
Electricity produced by the CHP unit and sold to the national grid	kWh	263,877.67	206,533.62
Heat produced by the CHP unit	MWh	317.00	238.58
Biogas supplied to the BioCNG unit	m^3	-	41,632.18
Electricity consumed by the BioCNG unit	kWh	-	23,126.40
Biomethane produced by the BioCNG unit	m^3	-	23,438.92
BIOMETHANE FARM TRACTOR	**UNIT**	**REFERENCE**	**AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS' OPERATION)**
Farm tractor	kg	0.14716[b]	0.20003[b]
Diesel consumption	$kg\ h^{-1}$	3.825	-
Biomethane consumed by the BioCNG tractor	$m^3\ h^{-1}$	-	6.08

Table 24. Annual outputs, fuel and energy consumption before and after the RES4LIVE interventions in the EV ILVO pilot farm (continued).

PVT & E-BOILER SYSTEM	UNIT	REFERENCE	AFTER INTERVENTIONS (FIRST YEAR OF RES SYSTEMS' OPERATION)
Electric boiler	p	-	0.10c[c]
PVT and solar station	p	-	0.04[d]
Electricity produced by the PVT system	kWh	-	2,520.00
Heat produced by the PVT system	kWh	-	8,886.00
Electricity used by the PVT system and accompanying equipment	kWh	-	228.00
Electricity consumed by the e-boiler	kWh	7,008.00	1,332.00
Grid electricity consumed by the e-boiler	kWh	7,008.00	0.00
Heat produced by the electric boiler	kWh	6,657.60	1,265.40
PVT electricity consumed by other farm facilities	kWh	-	1,188.00

[α] 1 piece of technology allocated to 15 years of lifetime
[b] 3760 kg of technology allocated to 20 years of lifetime
[c] 1 piece of technology allocated to 10 years of lifetime
[d] 1 piece of technology allocated to 25 years of lifetime

As in the case of the EV ILVO farm, the biogas upgrading plant and the BioCNG tractor were fully operational for part of the testing period. For the first one – and subsequently, the available BioCNG - the main obstacle was the delays in obtaining the necessary permissions for safe operation. As a result, the produced biogas was utilised primarily in the CHP unit. Again, the work conducted in T4.3 and T5.1, allowed us to confidently extrapolate the energy and fuel flows of interest.

Following the RES4LIVE interventions, the biogas digester now directs a portion of the biogas to the BioCNG unit (~26% during the first year of operation), rather than exclusively supplying the CHP unit with the entire biogas output. This change is reflected in the reduction of electricity and heat production by the CHP unit during this first year of operation, producing 78.27% and 75.26%, respectively, of the output compared to the reference year. In its first year of operation, the newly installed BioCNG unit processed 41,632.18 m³ of biogas and produced 23,438.92 m³ of BioCNG, while consuming 23,126.40 kWh of electricity.

During the first year of operation tests, the farm tractor, modified for BioCNG use, consumed on average approximately 6.08 m³ (or ~4.02 kg) of BioCNG per hour of operation. Annually, assuming an operational range of 2 to 5 hours per day, the expected total BioCNG consumption is estimated to be 7,767.2 m³ (5,138.00 kg). Before the retrofit, its diesel consumption for the same workload averaged 3.825 kg (0.0045 m³) per hour, resulting in an estimated annual diesel consumption of approximately 4,886.44 kg (~5.75 m³).

Finally, prior to the RES4LIVE interventions, the existing electric boiler consumed 7,008.00 kWh_{el} from the grid annually, providing approximately 6,657.60 kWh of thermal energy to the farm, assuming 95% efficiency. After the project's interventions, the boiler used only 1,332.00 kWh of grid electricity to provide 1,265.40 kWh_{th}. This reduction was due to utilising part of the 8,886.00 kWh of thermal energy produced by the PVT system.

In addition, the PVT system generated 2,520.00 kWh of electricity, covering the electric boiler's energy needs, with the surplus electricity being used in other facilities on the LVAT farm.

For detailed information on the Bill of Materials (BOM) for each unit comprising the integrated RES system installed at LVAT, please refer to Section A.4, "LVAT RES Systems BOM".

6.3 Impact assessment: Findings and discussion - LVAT

In the case of RES4LIVE interventions in the LVAT dairy cattle farm, the LCA results will be presented at the technology level. More particularly, their performance outcomes of the RS (years 2020-2022) and FYAIS (2023-2024) are compared at both midpoint and endpoint levels.

6.3.1 BioCNG impact assessment - LVAT

The uniqueness of this RES4LIVE intervention lies in the fact that it does not replace an existing system but rather adds a new feature—biogas upgrading—to the farm's capabilities. The following sections detail the environmental performance of the system itself, while a comparative analysis between the "CHP/diesel tractor" (RS) and the "CHP/BioCNG plant/BioCNG tractor" is provided in Section 6.3.3.

Midpoint level assessment

Table 33 presents the midpoint-level results from the environmental impact assessment of the FYAIS. The impact in the most significant categories—Climate Change, Particulate Matter, Water Use, and Fossil Fuel Resource Use—is quantified as 1.63 kg CO_2 equivalents, 1.03E-07 disease incidences, -0.25 m^3 of water deprivation, and -42.54 MJ, respectively. Notably, the system demonstrates a significant positive effect in reducing fossil fuel consumption, the primary goal of the intervention.

Table 33. Midpoint environmental impact assessment of 1 m^3 BioCNG production after-interventions system (FYAIS), expressed in unit EICI/1 m^3 BioCNG production.

EIC/ EICI	UNIT (per m^3 Biomethane at the gate of the BioCNG unit)	PERFORMANCE OF FYAIS
Climate change / GWP100	kg CO2 eq	1.629338
Particulate matter / DI	disease inc.	1.03E-07
Water use / WU	m^3 depriv.	-0.2479
Resource use, fossils / ADP-fossil	MJ	-42.5363
Land use / SQI	Pt	0.306035
Resource use, minerals and metals / ADP-ultimate reserve	kg Sb eq	-6.4E-07
Ozone depletion / ODP	kg CFC11 eq	-6.9E-08
Acidification / AE-AC	mol H+ eq	0.001292
Ionising radiation / IRP	kBq U-235 eq	0.021583
Photochemical ozone formation / POCP	kg NMVOC eq	-0.00667
Eutrophication, terrestrial / AE-TE	mol N eq	0.063118
Eutrophication, marine / NE	kg N eq	6.53E-05
Eutrophication, freshwater / PE	kg P eq	3.97E-05
Human toxicity, cancer / CTU-hc	CTUh	-2.1E-09

Table 25. Midpoint environmental impact assessment of 1 m³ BioCNG production after-interventions system (FYAIS), expressed in unit EICI/1 m³ BioCNG production.

EIC/ EICI	UNIT (per m³ Biomethane at the gate of the BioCNG unit)	PERFORMANCE OF FYAIS
Ecotoxicity, freshwater / CTUe	CTUe	-5.43853
Human toxicity, non-cancer / CTU-hc	CTUh	2.26E-09

Endpoint level assessment

Figure 27 ***and***

Table **34** present the single score results for the FYAIS across the studied environmental impact categories. The total environmental impact of integrating and operating the BioCNG plant at the farm is estimated at 7.59 mPt/m³ bioCNG following the interventions. The greatest positive impact is observed in the reduction of fossil fuel resource use (~ -54.44 μPt), while the category where the BioCNG system performs worst is climate change (~ 45.43 μPt), followed by particulate matter (~ 15.47 μPt).

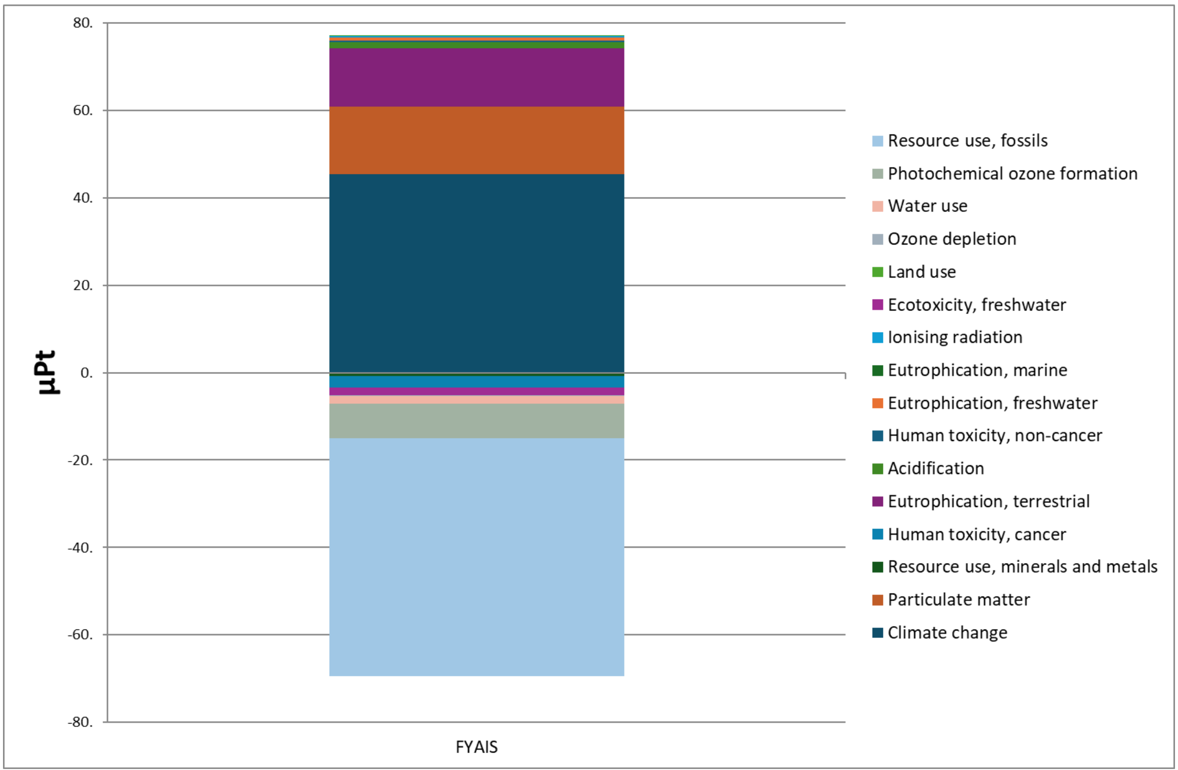

Figure 27. Single environmental score (SES) of 1 m³ BioCNG production after interventions system (FYAIS), expressed in unit EICI/1 m³ BioCNG production.

Table 34. Single environmental score (SES) per 1 m³ BioCNG production after interventions system (FYAIS) for each EICI.

DAMAGE CATEGORY	UNIT	FYAIS IMPACT
Climate change	µPt	45.43027583
Particulate matter	µPt	15.47303275
Water use	µPt	-1.839497667
Resource use, fossils	µPt	-54.4428629
Land use	µPt	0.029651311
Resource use, minerals and metals	µPt	-0.764459604
Ozone depletion	µPt	-0.082798521
Acidification	µPt	1.441805514
Ionising radiation	µPt	0.256227685
Photochemical ozone formation	µPt	-7.797884781
Eutrophication, terrestrial	µPt	13.24820885
Eutrophication, marine	µPt	0.098892536
Eutrophication, freshwater	µPt	0.692436184
Human toxicity, cancer	µPt	-2.632625635

Ecotoxicity, freshwater	µPt	-1.841080225

Table 26. Single environmental score (SES) per 1 m³ BioCNG production after interventions system (FYAIS) for each EICI (continued).

DAMAGE CATEGORY	UNIT	FYAIS IMPACT
Human toxicity, non-cancer	µPt	0.322742178
Total	**µPt**	**7.592063**

6.3.2 Farm tractor impact assessment - LVAT

Midpoint level assessment

Figure 28 presents the midpoint-level results from the comparative assessment of the FYAIS and RS systems. The results indicate that the FYAIS outperforms the RS in nearly half of the evaluated EICIs. In some cases, the FYAIS shows a significant advantage. For instance, in the categories of water use, fossil fuel consumption, and ozone depletion, the new system demonstrates environmental performance improvements of approximately 3.24, 2.03, and 2.01 times, respectively, compared to the diesel tractor.

Conversely, in categories such as particulate matter, ionising radiation, and freshwater eutrophication, the FYAIS performs worse, with impacts 2.18, 2.11, and 3.86 times greater, respectively. Additionally, the potential environmental impact related to climate change and the use of mineral and metal resources increased by 45.37% and 93.13%, respectively.

The increased environmental impact of the new tractor's operation is primarily due to the use of biogas (and consequently biomethane) derived from cattle manure. Essentially, it "carries" the environmental burden of the manure substrate, as a waste output of the dairy cattle milk supply chain. Consequently, the environmental performance of the tractor’s operation is directly dependent on the approach that was used to allocate the environmental burden of the cow-milk production chain on the manure that is excreted by cattle. In this case, not all the burden from the cow-milk production was allocated to the manure (e.g. GHG and ammonia housing emissions due to enteric fermentation and manure excretion as well as the environmental burden from material inputs important for milk production such as feed), however all emissions due to slurry storage are considered and fully allocated to this manure input. It is important to consider that when biogas production is involved, manure is an important co-product of the cow-milk supply chain system, and its environmental burden requires dedicated study. In RES4LIVE, such a study was considered out of the scope. In addition, if the biogas was based on a different substrate, the environmental profile would likely differ.

Thus, it cannot be neglected that if a proper allocation approach was performed with regards to the environmental burden of the cattle slurry substrate input to the biogas digester, the effect on the environmental profile could be positive for more EICIs.

The overall comparative environmental performance of the two systems will become clearer in the following section.

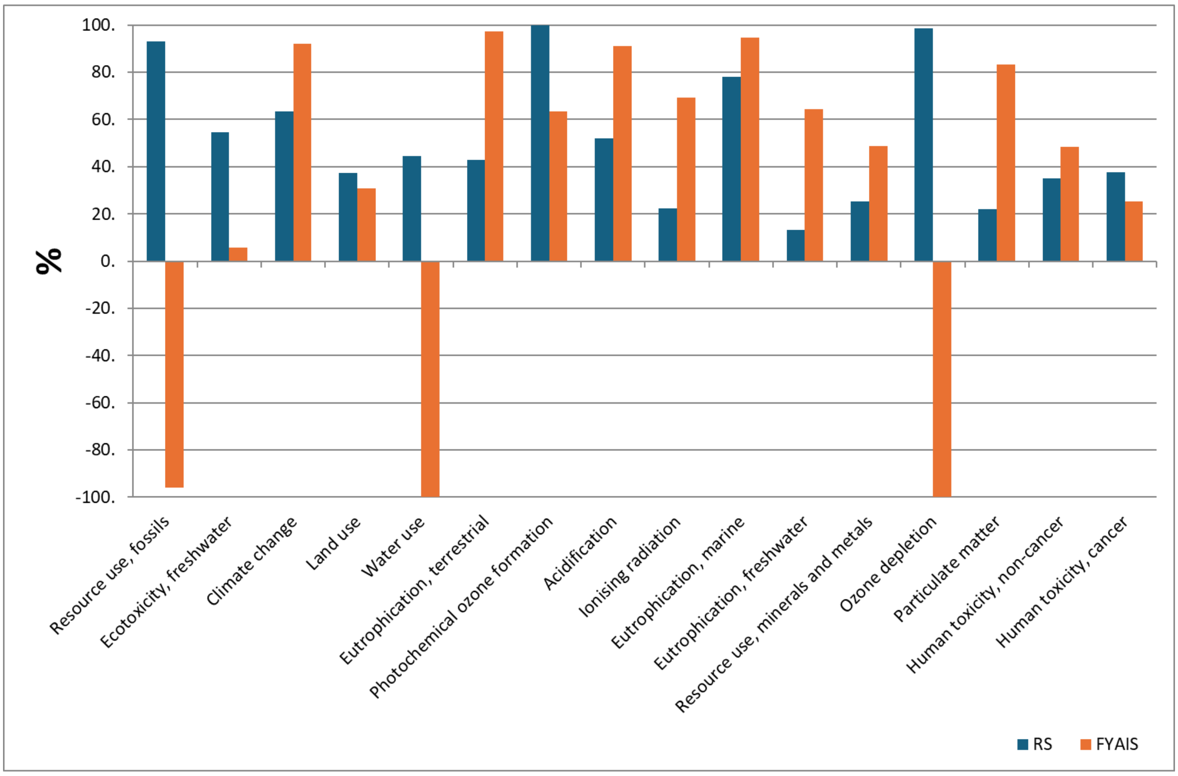

Figure 28. Midpoint environmental impact assessment of 1h of on-farm operation in the reference system (RS) vs the after-interventions system (FYAIS).

The absolute difference of the EICI values between the FYAIS and the RS are shown in Table 35, in addition to the relative % differences presented in Figure 28.

Table 35. Difference in midpoint EICIs for 1h of on-farm tractor operation between the after-interventions system (FYAIS) and the reference system (RS).

EIC / EICI	UNIT (per h of tractor's on-farm operation)	DIFFERENCE IN EICI VALUE
Climate change / GWP100	kg CO2 eq	7.71211963
Particulate matter / PI	disease inc.	6.54102E-07

Water use / WU	m^3 depriv.	-1.451320792
Resource use, fossils / ADP-fossil	MJ	-443.5379669
Land use / SQI	Pt	-2.953674601

Table 27. Difference in midpoint EICIs for 1h of on-farm tractor operation between the after-interventions system (FYAIS) and the reference system (RS) (continued).

EIC / EICI	UNIT (per h of tractor's on-farm operation)	DIFFERENCE IN EICI VALUE
Resource use, minerals and metals/ ADP-ultimate reserve	kg Sb eq	4.0002E-05
Ozone depletion / ODP	kg CFC11 eq	-6.44057E-07
Acidification / AE-TE	mol H+ eq	0.060194917
Ionising radiation / IRP	kBq U-235 eq	0.121227614
Photochemical ozone formation / POCP	kg NMVOC eq	-0.04365583
Eutrophication, terrestrial / AE-TE	mol N eq	0.471306348
Eutrophication, marine / NE	kg N eq	0.007212136
Eutrophication, freshwater / PE	kg P eq	0.00030283
Human toxicity, cancer / CTU-hc	CTUh	-1.49537E-08
Ecotoxicity, freshwater / CTUe	CTUe	-24.75372377
Human toxicity, non-cancer / CTU-hnc	CTUh	1.89259E-08

Endpoint level assessment

Figure 29 and Table 36 compare the SES attributed to the studied EICs between the RS and FYAIS. The total SES decreased by 0.11 mPt after the interventions, indicating a potential reduction of 8.61% in the overall environmental burden in the FYAIS.

Differences are also observed in the relative contribution of various EICs to the total SES of the two systems. For the diesel tractor, the most contributing categories are climate change (37.08%), fossil fuel resource use (21.87%), and photochemical ozone formation (10.96%). In contrast, for the BioCNG system, although climate change remains the largest contributor, with an increased share of

58.98%, terrestrial eutrophication (15.12%) and acidification (13.34%) follow, largely due to the impact of manure-based biogas.

Fossil fuel resource use, climate change, terrestrial eutrophication and particulate matter are the EICIs whose differences in SES largely define the difference in the total SES between the FYAIS and the RS.

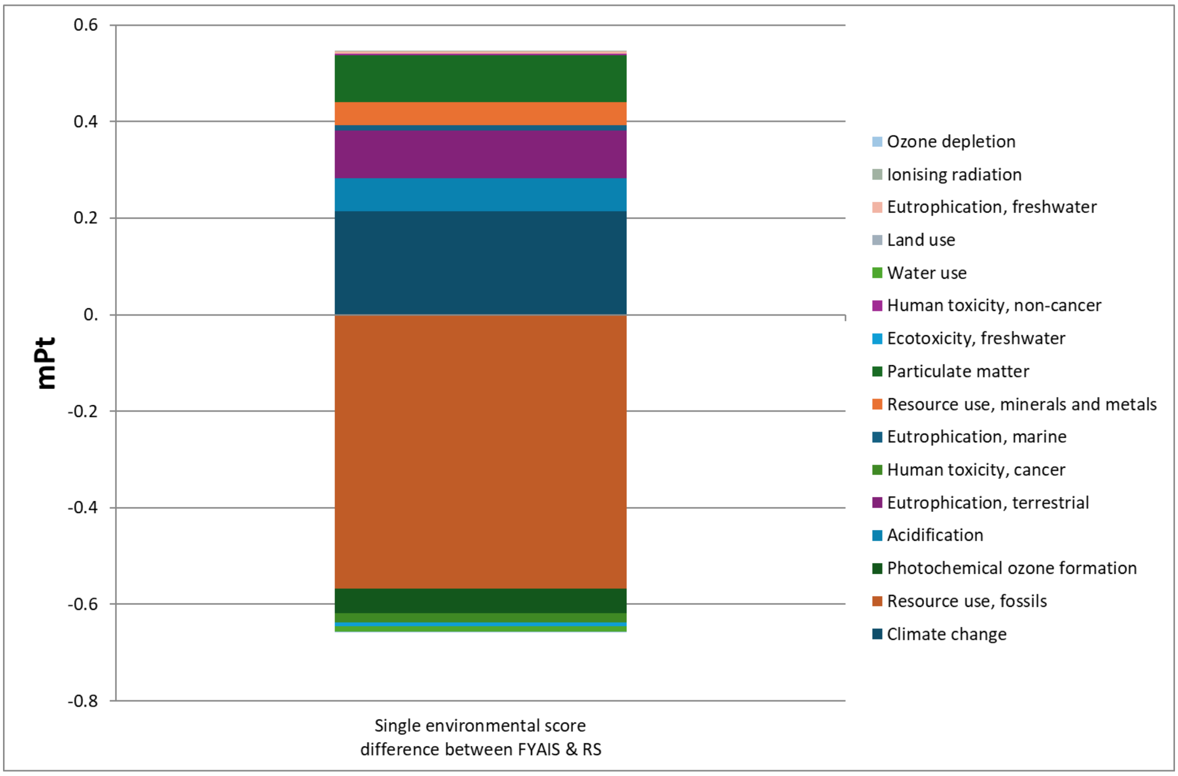

Figure 29. Difference in the Single environmental score (SES) 1h of on-farm operation between the after interventions system (FYAIS) and the reference system (RS).

Table 36. Difference in the Single environmental score (SES) per 1h of tractor's on-farm operation between the after interventions system (FYAIS) and the reference system (RS) for each EICI.

EIC	UNIT (per h of tractor's on-farm operation)	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL DIFFERENCE IN SES (%)
Climate change	µPt	0.215034	-195.37
Particulate matter	µPt	0.098439	-89.44
Water use	µPt	-0.01077	9.78

Resource use, fossils	µPt	-0.56769	515.79
Land use	µPt	-0.00029	0.26

Table 28. Difference in the Single environmental score (SES) per 1h of tractor's on-farm operation between the after interventions system (FYAIS) and the reference system (RS) for each EICI (continued).

EIC	UNIT (per h of tractor's on-farm operation)	DIFFERENCE IN SES	CONTRIBUTION TO THE TOTAL DIFFERENCE IN SES (%)
Resource use, minerals and metals	µPt	0.04747	-43.13
Ozone depletion	µPt	-0.00078	0.71
Acidification	µPt	0.067161	-61.02
Ionising radiation	µPt	0.001439	-1.31
Photochemical ozone formation	µPt	-0.05107	46.40
Eutrophication, terrestrial	µPt	0.098925	-89.88
Eutrophication, marine	µPt	0.010922	-9.92
Eutrophication, freshwater	µPt	0.005277	-4.79
Human toxicity, cancer	µPt	-0.01846	16.77
Ecotoxicity, freshwater	µPt	-0.00838	7.61
Human toxicity, non-cancer	µPt	0.002705	-2.46

Total	**µPt**	**-0.11006**	**100**

6.3.3 CHP/ Diesel tractor vs CHP/ BioCHP Plant/ BioCNG Tractor: Combined systems impact assessment - LVAT

To illustrate the potential environmental benefit of the biogas/BioCNG-related interventions in the LVAT pilot farm, an annual operation scenario comparing the combined operation of the:

- "CHP/ Diesel tractor system" (RS), and
- "CHP/BioCHP Plant/BioCNG Tractor system" (FYAIS)

should be considered.

Since the Functional Units (FU) of each sub-system refer to:

- 1 kWh of electric energy production for the CHP unit
- 1 h of on-farm operation for the diesel and BioCNG tractor, and
- 1 m^3 of produced biomethane for the BioCNG unit

The obtained results for the SimaPro should be multiplied by the operation parameters on an annual basis. The following were assumed for an indicative year (Table **37**).

Table 37. Assumptions for the annual operation of the combined system during the reference year (RS) and the first year after the interventions (FYAIS).

SUB-SYSTEM	UNITS	VALUE
CHP unit (RS)	kWh	263,877.67
CHP unit (FYAIS)	kWh	206,533.62
BioCNG (RS)	m^3	0.00
BioCNG (FYAIS)	m^3	23,438.92
Diesel tractor (RS)[a]	h	1,277.50
BioCNG tractor (FYAIS)[a]	h	1,277.50
[a] *Assuming a daily operation of 3.5h*		

The comparison is conducted at the system equivalence scale (SES) level, as the individual subsystems were analysed using different functional units (FUs) based on their specific cases. This approach simplifies the process of aggregating their combined environmental impact.

The comparison (Figure 30 and Table 38) is conducted at the system level and by considering the total performance on an annual basis (and not expressed per FU), as the individual subsystems were analysed using different functional units (FUs) based on their specific cases. This approach allows the aggregation of the environmental performance and the estimation of the effect on the annual environmental performance of the combined extended system.

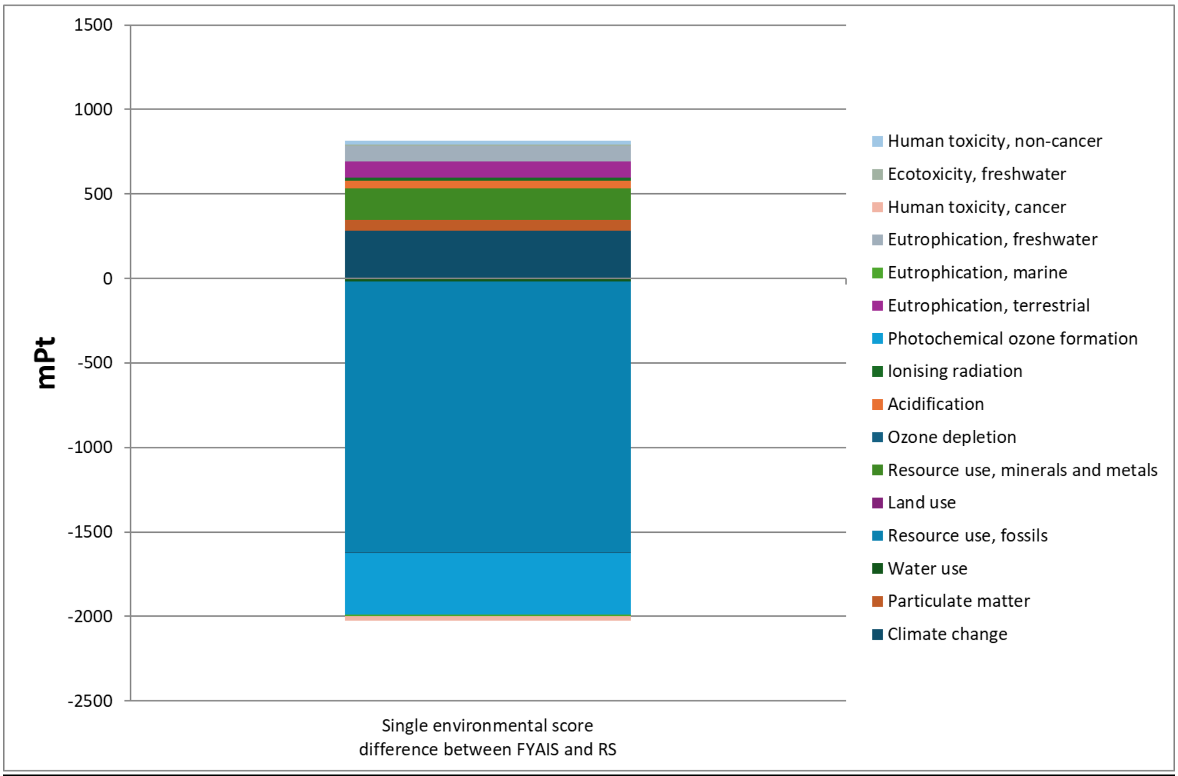

Figure 30. Difference in the Single environmental score (SES) between an indicative yearly operation of "CHP/Diesel tractor system" (RS) and "CHP/BioCHP Plant/BioCNG Tractor system" (FYAIS)

Table 38. Difference in the Single environmental score (SES) between an indicative yearly operation of "CHP/Diesel tractor system" (RS) and "CHP/BioCHP Plant/BioCNG Tractor system" (FYAIS) for each EICI.

EIC	UNIT (per year)	DIFFERENCE IN SES	CONTRIBUTION TO THE DIFFERENCE IN SES (%)
Climate change	mPt	284.47	-23.46
Particulate matter	mPt	60.34	-4.98
Water use	mPt	-15.84	1.31
Resource use, fossils	mPt	-1,605.80	132.42
Land use	mPt	2.49	-0.21

Resource use, minerals and metals	mPt	188.11	-15.51

Table 30. Difference in the Single environmental score (SES) between an indicative yearly operation of "CHP/Diesel tractor system" (RS) and "CHP/BioCHP Plant/BioCNG Tractor system" (FYAIS) for each EICI (continued).

EIC	UNIT (per year)	DIFFERENCE IN SES	CONTRIBUTION TO THE DIFFERENCE IN SES (%)
Ozone depletion	mPt	-2.69	0.22
Acidification	mPt	42.36	-3.49
Ionising radiation	mPt	18.40	-1.52
Photochemical ozone formation	mPt	-365.91	30.17
Eutrophication, terrestrial	mPt	95.98	-7.91
Eutrophication, marine	mPt	-7.69	0.63
Eutrophication, freshwater	mPt	90.92	-7.50
Human toxicity, cancer	mPt	-28.65	2.36
Ecotoxicity, freshwater	mPt	9.39	-0.77
Human toxicity, non-cancer	mPt	21.46	-1.77
Total	**mPt**	**-1,212.67**	**100.00**

A considerable decrease is marked in ozone depletion (4.5 times lower) and fossil resources use (-110.33%) impact categories compared to RS, an increase of 71.56% and 45.63% is marked in the human toxicity (non-cancer) and use of mineral and metal resources categories. Overall, a difference of 1,212.67 mPt is observed in the SES of the two systems, leading to a 20.55% potential improvement in the environmental performance of the combined system, after the interventions.

6.3.4 PVT/ electric boiler impact assessment - LVAT

Finally, the midpoint level assessment for the integration of the PVT system is presented below. Figure 31 shows the midpoint-level results from the comparative assessment of FYAIS and RS. The results suggest that the FYAIS outperforms the RS in all EICIs, except ADP-ultimate reserve (84.59% increase), and CTU-hnc (11.92% increase). Particularly, there is a considerable reduction in the GWP100 (108.56%), as well as the ADP-fossil (112.14%). Also, both DI and WU decreased by approximately 36%. IRP and AE-TE decreased by 116.35% and 113.49%, respectively.

Although the introduction of the new systems—due to raw materials and manufacturing—adds to the environmental burden, the FYAIS demonstrates improved environmental performance per kWh of thermal energy production.

Midpoint level assessment

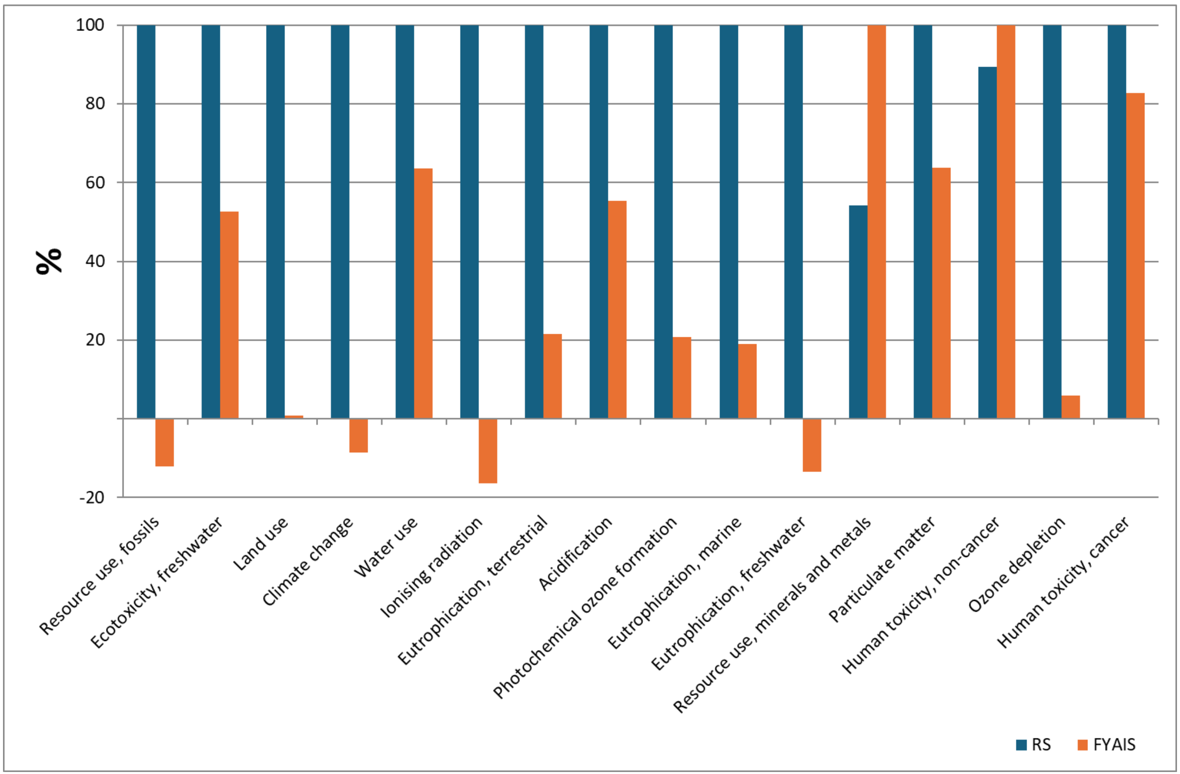

Figure 31. Midpoint environmental impact assessment of 1 kWh of thermal energy produced in the reference system (RS) vs the after interventions system (FYAIS).

Table 39 presents the absolute differences in the annual values of EICIs (per kWh of thermal energy produced by the electric boiler), in addition to the relative % differences shown in Figure 31.

Table 39. Difference in midpoint EICIs for 1 kWh of thermal energy produced between the after-interventions system (FYAIS) and the reference system (RS).

EIC / EICI	UNIT (per kWh of thermal energy produced by the electric boiler)	DIFFERENCE IN EICI VALUE
Climate change / GWP100	kg CO2 eq	-0.463494329
Particulate matter / DI	disease inc.	-2.32996E-09
Water use / WU	m^3 depriv.	-0.021593955
Resource use, fossils / ADP-fossil	MJ	-7.365302119
Land use / SQI	Pt	-1.908949334
Resource use, minerals and metals / ADP-ultimate reserve	kg Sb eq	4.53084E-06
Ozone depletion / ODP	kg CFC11 eq	-5.08564E-09
Acidification / AE-AC	mol H+ eq	-0.000556995
Ionising radiation / IRP	kBq U-235 eq	-0.027412566
Photochemical ozone formation / POCP	kg NMVOC eq	-0.000611858
Eutrophication, terrestrial / AE-TE	mol N eq	-0.001886684
Eutrophication, marine / NE	kg N eq	-0.0001652
Eutrophication, freshwater / PE	kg P eq	-6.70225E-05
Human toxicity, cancer / CTU-hc	CTUh	-3.0095E-10
Ecotoxicity, freshwater / CTUe	CTUe	-1.034154611
Human toxicity, non-cancer / CTU-hnc	CTUh	7.20625E-10

Endpoint level assessment

Figure 32 and Table **40** compare the SES attributed to the studied EICs between the RS and FYAIS. The total SES decreased by 21.77 µPt after the interventions (-59.74%), indicating a reduction in the overall environmental burden in the FYAIS.

The increase in SES for most of the environmental impact categories reviewed in the previous section led to a rearrangement of the most contributing of them in the FYAIS. In RS, climate change was contributing by 0.33%, while the use of resources (fossil fuels, minerals and metals) by 0.41%. In the FYAIS, these changes in the use of mineral and metal resources cover almost 80% of the overall environmental impact. Contrarily, the use of fossil fuel resources has a positive contribution to the environmental burden (~ -7%). Nevertheless, the changes in the SES attributed to climate change, the use of fossil fuel resources and the use of mineral and metal resources were found to be the most responsible for the change in the total SES between FYAIS and RS.

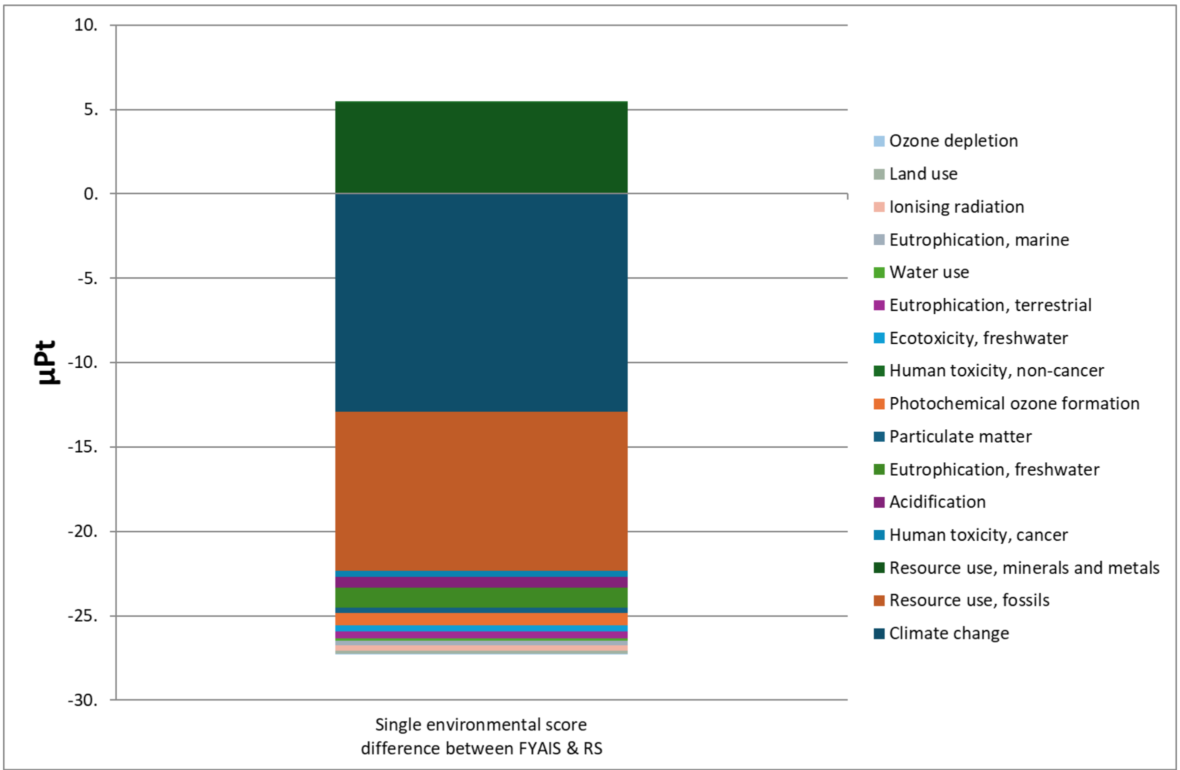

Figure 32. Difference in the Single environmental score (SES) kg of finished pigs' live weight at the farm gate between the after-interventions system (FYAIS) and the reference system (RS).

Table 40. Difference in the Single environmental score (SES) per kWh of thermal energy produced by the electric boiler between the after-interventions system (FYAIS) and the reference system (RS) for each EIC.

EIC	UNIT (per kWh of thermal	DIFFERENCE	CONTRIBUTION TO THE

	energy produced by the electric boiler)	IN SES	TOTAL DIFFERENCE IN SES (%)
Climate change	µPt	-12.92345174	59.36
Particulate matter	µPt	-0.350647846	1.61
Water use	µPt	-0.160231256	0.74
Resource use, fossils	µPt	-9.426968932	43.30
Land use	µPt	-0.184955355	0.85
Resource use, minerals and metals	µPt	5.376679497	-24.70
Ozone depletion	µPt	-0.006130154	0.03
Acidification	µPt	-0.621449775	2.85
Ionising radiation	µPt	-0.325430422	1.49
Photochemical ozone formation	µPt	-0.715794979	3.29
Eutrophication, terrestrial	µPt	-0.396005647	1.82
Eutrophication, marine	µPt	-0.250185219	1.15
Eutrophication, freshwater	µPt	-1.167891733	5.36
Human toxicity, cancer	µPt	-0.371544961	1.71

Table 32. Difference in the Single environmental score (SES) per kWh of thermal energy produced by the electric boiler between the after-interventions system (FYAIS) and the reference system (RS) for each EIC (continued).

EIC	UNIT (per kWh of thermal	DIFFERENCE	CONTRIBUTION TO THE

	energy produced by the electric boiler)	IN SES	TOTAL DIFFERENCE IN SES (%)
Ecotoxicity, freshwater	µPt	-0.350087511	1.61
Human toxicity, non-cancer	µPt	0.102997876	0.47
Total	**µPt**	**-21.77109816**	**100**

7 CONCLUSIONS

The key findings from the conducted Life Cycle Assessment (LCA), estimating the environmental impact of the RES4LIVE technologies after one year of operation (FYAIS) compared to a reference year (RS) are summarised below.

The results show a slight increase in environmental impact per kg of sow at the hog barn gate after installing new technologies in the GOLINELLI hog barn. The total environmental impact rose by 0.024 mPt (1.89%). This increase mainly stems from higher electricity consumption and the need for new materials for the systems. While operational efficiency improved, the overall environmental burden was higher in the first year of technologies' operation. Looking ahead, future changes—especially regarding thermal losses—could lead to better results over time.

In the nursery barn, the total SES per kg of weaned piglet at the nursery barn gate decreased by 13.65 μPt (-4.06%), indicating a reduction in the overall environmental burden. This decrease is largely due to the elimination of LPG use, a modest rise in electricity consumption, and increased reliance on renewable energy. The four RES technologies installed had a minimal contribution to the total environmental impact, accounting for just 0.21% (~0.68 μPt). Specifically, the PVT system contributed 0.145% (0.042 μPt), the BTES 0.013% (0.103 μPt), the heat pump 0.032% (0.467 μPt), and the smart control system 0.021% (0.069 μPt).

At the EV ILVO farm, the total environmental impact saw a decrease of 78.14 μPt per kg of finished pig at the housing gate (-11.53%) after the interventions. The reduction in fossil fuel resource use mainly due to the elimination of natural gas use was a key driver of the overall improvements. The use of renewable energy sources helped offset a modest rise in grid electricity consumption. The contribution from the installed RES technologies was negligible, making up only 0.29% (0.296 μPt) of the total environmental burden for the FYAIS. The PVT system contributed 0.222% (1.329 μPt), the heat pumps 0.049%, and the smart control system 0.018% (0.109 μPt).

The total SES at the AUA poultry farm increased by 57.68 μPt per kg of egg at the housing gate, indicating a rise in the overall environmental burden after the interventions, mostly due to the important increase in electricity consumption. Two additional scenarios, which involved using smaller exhaust fans, demonstrated lower impacts compared to the FYAIS, highlighting opportunities for further optimization. For instance, GWP100 decreased by between 10.03 μPt and 12.79 μPt due to reduced electricity consumption.

The integration of a BioCNG plant at the LVAT farm resulted in an estimated total environmental impact of 7.59 mPt per m^3 of biomethane at the gate of the bioCNG unit. The most notable benefit was a reduction in fossil fuel resource use (-54.44 μPt) due to the replacement of diesel fuel for transport purposes, but this was offset by significant increases in the contribution of GWP100 (Climate Change EIC) (45.43 μPt) and DI (Particulate Matter EIC) (15.47 μPt) to the total SES, mostly associated with the use of cattle slurry as a substrate for biogas production. Switching from a diesel tractor to a BioCNG-powered tractor led to a total environmental impact decrease of 0.11 mPt per h of on-farm tractor operation (-8.61%). While climate change and fossil fuel resource use remained major contributors to the total SES of the systems compared, the share of climate change impact increased to 58.98%, largely due to this type of biogas usage. Comparing the two combined CHP/fuel/tractor systems further showed a 20.55% reduction in the total annual environmental performance following the interventions. Fossil resource use contribution to the SES decreased nearly by 110%, the contributions of human toxicity (non-cancer) and minerals and metals resource use increased by 71.56% and 45.63%, respectively. Finally, integrating a PVT system and e-boiler at the LVAT farm resulted in a 21.77 µPt reduction per kWh of thermal energy produced by the e-boiler (-59.74%) in the total SES, increasing the environmental performance of heat supply by the e-boiler.

Overall, the LCA results indicate that introducing new technologies in intensive livestock facilities can lead to positive environmental outcomes. Reductions in the overall environmental impact were notably observed in the GOLINELLI nursery barn, EV ILVO farm, and various components of the LVAT systems. However, the AUA poultry farm and GOLINELLI hog barn experienced increases in key impact categories like climate change and resource use. Improvements such as eliminating fossil fuels, reducing water use, and enhancing feed efficiency have had positive effects. Still, increased electricity consumption and the material demands for new systems sometimes offset these gains. Future optimization efforts should prioritize reducing energy consumption, improving material efficiency, and continuing the transition toward renewable energy sources.

ANNEX – RES4LIVE SYSTEMS BILLS OF MATERIALS (BOM)

A.1 GOLINELLI RES Systems BOM

A.1.1 Multi-source Heat Pump BOM (Nursery barn - B.16)

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
HEAT PUMP & ACCOMPANYING EQUIPMENT (GOLINELLI)	Heat Pump Housing	Cover	Mid-low carbon steel
	Digital Scroll Compressor	Scroll elements Motor Housing and Frame	Cast iron
		Bearings	Stainless steel
		Shaft and Crankshaft	Hardened steel
		Seals and Gaskets	Plastics
		Fasteners	Steel
		Refrigerant	R407C
		Oil	POE-32
	Heat exchangers	Evaporator	Stainless steel
			Copper
		Air-cooled Evaporator	Copper
			Aluminium
		Condenser	Stainless steel
			Copper
	Expansion valve	Electronic Thermostatic Expansion Valve	Brass
			Stainless steel
	Other components	Accumulator/ Subcooler	Stainless steel
		Expansion Tank	Stainless steel
		Receiver	Stainless steel

HEAT PUMP & ACCOMPANYING EQUIPMENT (GOLINELLI)	Other components	Filter Dryer	Cast iron
			Ceramics
		Hot gas Valve	Brass
			Stainless steel
		4-way valve	Brass
		Axial fan	Steel
	Sensors	Pressure Transmitter	Stainless Steel
		Temperature Sensor NTC	Manganese
			Epoxy
		Temperature Sensor PT100	Platinum
	Control	Inverter	Electronics
		PLC	Electronics
		Electric panel	Cast iron
		Cables	Copper
			PVC
	Piping and instrumentation	Copper for refrigerant	Copper
		Insulation	Rubber foam
		Water pump	Cast iron
			Bronze
			Stainless steel
			Plastic
		Solenoid Valves	Brass
			Copper
			Stainless Steel
			Plastics
		Ball Valve	Bronze

HEAT PUMP & ACCOMPANYING EQUIPMENT (GOLINELLI)	Piping and instrumentation	Water Check valve	Brass
		Water Ball valve	Brass
		Flow switch	Stainless steel
		Liquid Indicator	Stainless steel
		Pipes	Polyethylene
		Insulation	Flexible elastomeric foam
	Working fluid		Glycol
			Water

A.1.2 PVT and Solar Station System BOM (Nursery barn - B.16)

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
PHOTOVOLTAIC-THERMAL SYSTEM, SOLAR STATION & ACCOMPANYING EQUIPMENT (GOLINELLI)	PVT Collectors	PV collector	Glass
			Polymers
			Aluminum
			Monocrystalline Silicon
			Copper
			Antimony
			Silver
			Zinc
			Lead
			Tin
		Thermal collector	Aluminum
			Copper
	Inverter		Electronics

PHOTOVOLTAIC-THERMAL SYSTEM, SOLAR STATION & ACCOMPANYING EQUIPMENT (GOLINELLI)	Hydraulics, piping & Instrumentation		Steel
			Stainless steel
			Brass
			Plastic
			Polyethylene
			Electronics
	Sensors		Platinum
	Pumps		Cast iron
			Bronze
			Stainless steel
			Plastic
	Electric components	Miscellaneous cables	Copper
			PE
			PVC
			Polycarbonate
			Plastic
			Steel
			Silicone
			Electronics
			Transformers
	Cabinet enclosure	Cover	Steel
		Pipes	Polyethylene
		Insulation	Flexible elastomeric foam
	Working fluid		Glygol
			Water

A.1.3 BTES System BOM (Nursery barn - B.16)

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
BOREHOLE THERMAL ENERGY STORAGE SYSTEM (GOLINELLI)	Probes, Piping, Fittings		Polyethylene
	Probes		Iron
	Piezometers		PVC
	Weights		Iron
	Misc metal fittings		Brass
			Steel
	Insulation		Flexible elastomeric foam
	Filling Material		Thermal grout
			Standard grout
			Gravel drainage (4-16 mm)
			Concrete
	Geotextile		Nonwoven fabric
	Working fluid		Glygol
			Water

A.1.4 Envelope Retrofit (Windows) BOM (Hog Barn - B.12)

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
HOG BARN RETROFIT (GOLINELLI)	Windows	Stainless steel	
		Polycarbonate	
		Steel	
	Gearmotors	Cast iron	
		Copper	
		Steel	

HOG BARN RETROFIT (GOLINELLI)	Gearmotors	Hardened Steel
		Lamination steel
		Plastics

A.1.5 Smart Control System BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
SMART CONTROL SYSTEM (GOLINELLI)	Gateway	Raspberry Pi	Electronics
	Energy meters	Display Panel Display Panel Protective Coverings Seals and Gaskets	Plastic
		Current/ Voltage Transformers	Iron
		Circuit Board	Printed Circuit Board (PCB)
		Energy Measurement	Electronic Components
		Wiring and Connectors	Copper
		Fasteners and Screws	Steel
	Misc sensors	Misc Sensors	
	Weather station	Solar panel	PV cells
		Battery	6600 mAh rechargeable battery
		Main body and Sensors	Plastic
			Printed Circuit Board (PCB)
			Copper
			Stainless Steel

A.2 EV ILVO RES Systems BOM

A.2.1 Multi-source Heat Pumps BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
HEAT PUMPS & ACCOMPANYING EQUIPMENT (ILVO)	Heat Pump Housing	Cover	Mid-low carbon steel
	Digital Scroll Compressor MTHP Digital Scroll Compressor HTHP	Scroll elements Motor Housing and Frame	Cast iron
		Bearings	Stainless steel
		Shaft and Crankshaft	Hardened steel
		Seals and Gaskets	Plastics
		Fasteners	Steel
		Refrigerant	R407C
		Oil	POE-32
	Heat exchangers	MTHP Condenser/ Evaporator HTHP Condenser/ Evaporator	Stainless steel
			Copper
		Dry cooler	Copper
			Aluminium
			Mid-low carbon steel
			Aluminium
			Steel
	MTHP Expansion valve HTHP Expansion valve	Electronic Thermostatic Expansion Valve	Brass
			Stainless steel
	Other components	Subcooler	Copper
		Accumulator/ Subcooler	Stainless steel
			Copper

	Other components	Expansion Tank	Stainless steel
HEAT PUMPS & ACCOMPANYING EQUIPMENT (ILVO)	Other components	Buffer Tank	Steel
		Filter Dryer	Cast iron
			Ceramics
		4-way valve	Brass
		3-way valves	Bronze
	Sensors	Pressure Transmitter	Stainless Steel
		Temperature Sensor NTC	Manganese
			Epoxy
		Temperature Sensor PT100	Platinum
	Control	Inverter	Electronics
		PLC	Electronics
		Electric panel	Cast iron
		Cables	Copper
			PVC
	Piping and instrumentation	Copper for refrigerant	Copper
		Insulation	Rubber foam
		PEX-AL-PEX Pipes	Polyethylene
			Aluminium
		Water pumps	Cast iron
			Bronze
			Stainless steel
			Plastic
		Solenoid Valves	Brass
			Copper
			Stainless Steel
			Plastics

HEAT PUMPS & ACCOMPANYING EQUIPMENT (ILVO)	Piping and instrumentation	Valves	Bronze
		Water Check valve	Brass
		Flow switch	Stainless steel
		Liquid Indicator	Stainless steel
	Working fluid		Glycol
			Water

A.2.2 PVT and Solar Station System BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
PHOTOVOLTAIC-THERMAL SYSTEM, SOLAR STATION & ACCOMPANYING EQUIPMENT (ILVO)	PVT Collectors	PV collector	Glass
			Polymers
			Aluminum
			Monocrystalline Silicon
			Copper
			Antimony
			Silver
			Zinc
			Lead
		Thermal collector	Aluminum
			Copper
	Inverter		Electronics
	Hydraulics, piping & Instrumentation		Steel
			Stainless steel
			Brass
			Plastic
			St. Steel Pipes

PHOTOVOLTAIC-THERMAL SYSTEM, SOLAR STATION & ACCOMPANYING EQUIPMENT (ILVO)	Hydraulics, piping & Instrumentation	Copper & Copper Pipes
		Electronics
	Heat Exchanger	Stainless steel
		Copper
	Sensors	Platinum
	Pumps	Cast iron
		Bronze
		Stainless steel
		Plastic
	Elecrtric components	Copper
		PE
		PVC
		Polycarbonate
		Plastic
		Steel
		Electronics
		Transformers
		Silicone
	Cabinet enclosure	Steel
	Working fluid	Glycol
		Water

A.2.3 Smart Control System BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
SMART CONTROL SYSTEM (ILVO)	Gateway	Raspberry Pi	Electronics
	Energy meters	Display Panel Display Panel Protective Coverings Seals and Gaskets	Plastic
		Current/ Voltage Transformers	Iron
		Circuit Board	Printed Circuit Board (PCB)
		Energy Measurement	Electronic Components
		Wiring and Connectors	Copper
		Fasteners and Screws	Steel
	Misc sensors	Misc Sensors	
	Weather station	Solar panel	PV cells
		Battery	6600 mAh rechargeable battery
		Main body and Sensors	Plastic
			Printed Circuit Board (PCB)
			Copper
			Stainless Steel

A.3 AUA RES Systems BOM

A.3.1 Heat Pump and Ventilation System BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
HEAT PUMP & ACCOMPANYING EQUIPMENT (AUA)	Heat Pump Housing	Cover	Mid-low carbon steel
	Digital Scroll Compressor	Scroll elements Motor Housing and Frame	Cast iron
		Bearings	Stainless steel
		Shaft and Crankshaft	Hardened steel
		Seals and Gaskets	Plastics
		Fasteners	Steel
		Refrigerant	R407C
		Oil	POE-32
	Heat exchangers	Condenser Evaporator BPHE	Stainless steel
			Copper
		Evaporator/ Condenser- Air cooled	Copper
			Aluminium
		Recuperator	Copper
			Aluminium
		Subcooler	Copper
		Dry cooler (excl. pumps and fans)	Copper
			Aluminium
			Mid-low carbon steel
			Treated cellulose
	Fans	Dry cooler fans	Steel
		Centrifugal fan (unit)	Steel
		Centrifugal fan (ventilation)	Steel

HEAT PUMP & ACCOMPANYING EQUIPMENT (AUA)	Fans	Housing	Steel
		Centrifugal fan (ventilation)	Steel
		Housing	Steel
	Expansion valve	Electronic Thermostatic Expansion Valve	Brass
			Stainless steel
	Other components	Hot gas bypass regulator	Copper
			Stainless steel
		Dual flow filter	Cast iron
			Ceramics
		4-way valve	Brass
		Water pumps (4p)	Cast iron
			Bronze
			Stainless steel
			Plastic
	Sensors	Pressure sensor	Stainless Steel
		Temperature Sensor NTC	Manganese
			Epoxy
		Temperature Sensor PT100	Platinum
	Control	Inverter	Electronics
		PLC	Electronics
		Electric panel	Cast iron
		Cables	Copper
			PVC
	Piping and instrumentation	Copper for refrigerant	Copper
		Insulation	Rubber foam
		PVC water pipes	PVC

HEAT PUMP & ACCOMPANYING EQUIPMENT (AUA)	Piping and instrumentation	Insulation	Rubber foam
		Solenoid Valves	Brass
			Copper
			Stainless Steel
			Plastics
		Valves	Bronze
		Water Check valve	Brass
		Tee junction	Copper
		Liquid Indicator	Stainless steel
	AC/ Ventilation Channels	AC and Ventilation channel	Stainless steel
		Insulation	Rubber foam

A.3.2 PV System BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
PHOTOVOLTAICS & ACCOMPANYING EQUIPMENT (AUA)	PV system	PV collectors	Glass
			Polymers
			Aluminum
			Monocrystalline Silicon
			Copper
			Antimony
			Silver
			Zinc
			Lead
		Base for roof	Aluminium
	Inverter		Electronics
	Cabinet enclosure	Cover	Steel

PHOTOVOLTAICS & ACCOMPANYING EQUIPMENT (AUA)	Miscellaneous cables and electrical parts	Copper
		Zinc coated steel

A.3.3 LED Lighting System BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
LED LIGHTING SYSTEM (AUA)	LEDs	LED strips	Light emitting diodes
		LED cover	Aluminium
			Polybutadiene
	Controllers		Electronics
	Boxes	Cover	Polycarbonate

A.3.4 Smart Control System BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
SMART CONTROL SYSTEM (AUA)	Gateway	Raspberry Pi	Electronics
	Energy meters	Display Panel Protective Coverings Seals and Gaskets	Plastics
		Current/ Voltage Transformers	Iron
		Circuit Board	Printed Circuit Board (PCB)
		Energy Measurement	Electronics
		Wiring and Connectors	Copper
		Fasteners and Screws	Steel
	Environmental sensors		Electronics

SMART CONTROL SYSTEM (AUA)	Weather station	Solar panel	PV cells
		Battery	6600 mAh rechargeable battery
		Main body and Sensors	Plastic
			Printed Circuit Board (PCB)
			Copper
			Stainless Steel

A.4 LVAT RES Systems BOM

A.4.1 Biomethane Upgrading Unit and BioCNG Filling Station BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
BIOMETHANE UPGRADING UNIT & FILLING STATION (LVAT)	Heat Pump Housing	Cover	Steel
	Compressor	Enclosure (Housing, Inlet buffer tank, Condensate collecting tank)	Steel
		Motor	Stainless Steel
			Steel
			Copper
			Plastic
		Compressor	Stainless Steel
			Steel
			Plastic
	Membranes		Polyimide
			Polymer (e.g., PVC, ABS, PP)
			Elastomers (e.g., EPDM, FKM)
			Stainless Steel
	Filling station	Nozzle Bio-CNG storage bundle	Stainless Steel
			Brass
			Various Elastomers
			High-Strength Plastic
			Steel

	Misc. components	Flame arrester Condensate drain Particle filters Filter iron pellets Frequency-controlled gas compressor Gas Filter Plate heat exchangers Refrigerator Liquid separator Electric heater Radiators	Stainless Steel
			Steel
			Plastic
	Pipes and Valves	Ball/ Solenoid/ Drain/ Pressure reducing valves	Stainless Steel
			Plastic
		Suction line	Stainless Steel
	Sensors & Transmitters		Stainless Steel

A.4.2 Adapted Farm tractor for BioCNG Use BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
ADAPTED BIOCNG TRACTOR (LVAT)	CNG Storage	Covers	Aluminium
		CNG tanks	Carbon fibre reinforced plastic
		Straps for CNG Tanks	Steel
			Synthetic rubber
	High pressure pipping	High pressure pipes	Stainless steel
		Refuelling system	Stainless steel
		Gas regulator	Stainless steel
			Synthetic rubber
		Filtre (high pressure) Gas pressure regulator Heat exchanger	Stainless steel
			Aluminium

ADAPTED BIOCNG TRACTOR (LVAT)	Engine Control System (ECU) and assocoated components	Modified Diesel engine for Gas combustion	Steel
			Aluminium
		Engine Control Unit (ECU) system	Steel
			Electronics
		Ignition coil	Copper
			Steel
			Cables
		Gas injectors system	Aluminium
			Copper
			Synthetic rubber
			Electronics
		Engine speed and position system	Copper
			Aluminium
			Steel
		Air inlet system	Aluminium
			Steel
			Copper
			Synthetic rubber
			Plastics
	Exhaust line	Exhaust System	Stainless steel
			Steel
			Metal catalyst for catalytic converter
	Fluids	Lubricating oil	
		Engine cooling liquid	Glycol
			Water
		Refrigerant	R134a

A.4.3 PVT and Solar Station BOM

SYSTEM	COMPONENT/	PART	MAIN MATERIALS
PHOTOVOLTAIC-THERMAL SYSTEM, SOLAR STATION & ACCOMPANYING EQUIPMENT (LVAT)	PVT Collectors	PV collector	Glass
			Polymers
			Aluminum
			Monocrystalline Silicon
			Copper
			Antimony
			Silver
			Zinc
			Lead
		Thermal collector	Aluminium
			Glass
			Steel
			Copper
			Polyurethane
			Synthetic rubber
			Plastics
			Glass fibre
			Silicone
			Cables
			Diodes
			Sealing tape
	Inverter		Electronics
	Hydraulics, piping & Instrumentation		Steel
			Stainless steel
			Brass

PHOTOVOLTAIC-THERMAL SYSTEM, SOLAR STATION & ACCOMPANYING EQUIPMENT (LVAT)	Hydraulics, piping & Instrumentation		Copper
			Plastic
			Electronics
	Heat Exchanger		Stainless steel
			Copper
	Temperature sensors		Platinum
	Pumps	Pumps	Cast iron
			Bronze
			Stainless steel
			Plastic
	Electric components	Miscellaneous cables	Copper
			PE
			PVC
			Polycarbonate
			Plastic
		Miscellaneous parts	Steel
			Stainless steel
			Copper
			Plastics
			Silicone
	Cabinet enclosure		Steel
	Energy meters		Electronics
			Transformers
	Working fluid		Glycol
			Water

A.4.4 Barn Cooling System BOM

SYSTEM	COMPONENT/ PART	MAIN MATERIALS
BARN COOLING SYSTEM (LVAT)	Coolers	Steel
		Plastics
		Treated cellulose
		Water
	Ventilators	Steel
	Air Tubes	Polyester textile
	Bypass Boxes	Plywood
	Controllers and Sensors	Electronics

A.5 Draft datasets examples

A.5.1 Draft dataset example – Heat pump components

Component	***Manufacturer***	***Type***	***Material***	***Weight***	***Characteristics***	***Origin***	***More data***
Scroll Compressor	Copeland	ZH13KVE-TFD	Mainly Cast iron	38 kg	Displacement: 11.7 m^3/h	Denmark	https://climate.emerson.com/documents/copeland-scroll-zh-compressors-for-r410a-r407c-r134a-en-gb-4216112.pdf
Heat exchangers							
Condenser	SWEP	B25TH	Bronze and stainless steel	5.82 kg	Plates: 20, Heat load 6.7 kW	Sweden	Attached file
Economizer	SWEP	B5TH	Bronze and stainless steel	1.92-2.37 kg	Plates: 34, Heat load 0.33 kW	Sweden	Attached file
Evaporator-water cooled	SWEP	B25TH	Bronze and stainless steel	4.6-7.76 kg	Plates: 20, Heat load 5.55 kW	Sweden	Attached file
Evaporator- air cooled	PSYCTO		Copper tuber, aluminum fins	18 kg	Heat load: 6.15 kW	Greece	Attached file

A.5.2 Draft dataset example – PVT components

Category	P&ID drawing	Component description	Manufacturer	Model		Diameter/Connection	Quantity	Units
PVT Collectors	-	PVT Collector	Abora	aH72 SK, 350W	Number of cells 72 Weight 50 kg. Front glass 3,2 mm. tempered Framework Aluminum Cell type Mono-crystalline Rated power (W) 350 W Module efficiency (%) 17,8	N/A	24	Psc
Instrumentation	ILVO-Solar Circuit	Radiation sensor	Resol	CS10	40gr PA6 (cable gland) and PMMA (housing)	N/A	1	Pz
Instrumentation		Temperature transmitter	Resol	FKP6 (L1 45mm)	Pt1000	6 mm	2	Pz
Instrumentation		Inmersion sleeve	Resol	TH45 (L1 45mm) (Brass)	Brass 1kg	1/2"	2	Pz
Instrumentation		Temperature transmitter (ambient)	Resol	FAP13	130gr - plastic housing/ platinum measuring element.	N/A	1	Pz
Hydraulics and piping		Expansion Vessel 15 lt	Somatherm	AMR 15	steel - 4kg	DN 270 mm, height 320 mm	1	Pz
DAQ and Control		Solar central controller	Resol	MX	2kg	N/A	1	Pz
Instrumentation		Temperature indicator	Qvintus	Q 465-1	(Brass/ stainless steel) - 250gr	N/A	2	Pz
Instrumentation		Temperature transmitter	Resol	FKP5,5 (L1 28mm)	Pt1000	5.5 mm	2	Pz