UNIVERSITÀ DEGLI STUDI DI SASSARI

CORSO DI DOTTORATO DI RICERCA
Scienze Agrarie

Curriculum Scienze e Tecnologie Zootecniche

Ciclo XXIX

Eco-Sustainable Energy Consumption and Production in Animal Farming

dr. Elena Brundu

Coordinatore del Corso prof. Antonello Cannas
Referente di Curriculum prof. Gianni Battacone
Docente Guida prof. Antonio Pazzona

Anno accademico 2015- 2016

To Elisabetta

TABLE OF CONTENTS

ABSTRACT

Intensive animal farming is highly energy demanding and often associated with concerns for food quality and for the environment. Pursuing the general objectives of implementing reliable tools for energy use optimization and for green energy sources exploitation in animal farming, we investigated the energy consumption and production during a three year period in a study farm hosting a rooftop photovoltaic system and a mini-turbine.

Consumption data, collected by detection and in depth analysis of equipment involved in different production cycles, were used to develop and validate a mathematical optimization model, leading to significant energy and money savings through the replacement of actual with alternative and more energy efficient equipment.

Environmental parameters in the same animal farming context, with special regard to solar irradiation and wind speed, were surveyed and employed as input data to run specific simulation software applications that estimated the expected energy production levels of the photovoltaic and wind power systems. The output of these simulations, based on actual and estimated environmental data, was compared to the green energy produced in the farm, which allowed to quantify the deviation between actual and estimated values.

Everything considered, the application of this study approach on a larger scale will generate useful tools for farm management toward general economical benefits and a higher environmental responsibility.

RIASSUNTO

L'allevamento zootecnico intensivo comporta un elevato consumo energetico, spesso associato a preoccupazioni riguardanti qualità della carne e sostenibilità ambientale. Il presente studio si è posto gli obiettivi di sviluppare uno strumento per l'ottimizzazione dei consumi energetici e di verificare l'efficienza produttiva degli impianti fotovoltaico e mini-eolico in un sistema mediterraneo.

I dati sui consumi energetici associati a ciascun dispositivo e ciclo produttivo aziendale, rilevati durante un triennio, sono stati elaborati per lo sviluppo e la validazione di un modello matematico che ha permesso di identificare i dispositivi maggiormente energivori e di suggerire la loro sostituzione con altri più efficienti dal punto di vista energetico, determinando così un risparmio per l'azienda.

Lo studio delle produzioni mediante fotovoltaico ed eolico si è basato sul confronto tra i livelli rilevati e quelli ottenuti tramite simulazione impiegando sia dati ambientali (radiazione solare e velocità del vento) misurati durante il periodo sperimentale che dati probabilistici disponibili su diversi database. Gli scostamenti tra valori reali e stimati sono stati trascurabili per il fotovoltaico e più variabili per l'eolico.

In conclusione, l'applicazione di questo approccio allo studio su più larga scala consentirà di mettere a punto strumenti utili alla gestione aziendale finalizzata sia al beneficio economico che ad una maggiore responsabilità per l'ambiente.

STATE OF THE ART AND OBJECTIVES

1 INTRODUCTION

Intensive animal farming is a highly energy demanding activity that is often associated with concerns for the deriving food quality and for the environment (Petit and Hayo, 2003).

As stated by the Food and Agriculture Organization of the United States (FAO) in the recent report "World Livestock 2011: Livestock in food security", an increase in the use of large scale intensive animal breeding is predicted, as a consequence of the per capita protein consumption in developing countries.

To satisfy the food needs of a growing human population (Connelly, 2009) and to stay aligned with environment protection principles (De Schutter and Vanloqueren, 2011), it is vital to pursue sustainable animal husbandry purposes.

Hence, a more environmentally responsible intensive livestock production, is a primary objective to be achieved. A coherent approach is the implementation of innovative systems that allow animal production efficiency (Reilly and Willenbockel, 2010; Pulina et al. 2011).

If we refer to energy-related issues, it is possible to identify two main lines of action focused on pursuing the animal farming ecological and economical sustainability: 1) energy saving through the optimization of energy consumption, and 2) the implementation of green energy production systems, which results in a lower environmental impact.

In order to implement systems aimed at the optimization of energy consumption it is first necessary to conduct an in-depth analysis of farm equipment and operations that determine the use of energy. Once the energy demanding items have been identified they should be monitored so as to determine the consumption level on a day by day basis and over the year. To perform this task, specific tools need to be developed and made available to the farm managers and their consultants.

On the other side, the production of the energy necessary to satisfy the farm needs, may derive from renewable energy resources (Biondi et al., 1989; Riva, 1990). Given their availability, persistence and eco-compatibility (lack of emission of polluting substances) features, the interest on these “green energy” sources is significantly growing, according to the noble purpose of reducing Earth global pollution (Tilman, 1998; Tilman et al., 2001).

Research activities conducted during the last decades, led to the development of new technologies aimed at improving the exploitation of renewable energy resources, taking into account their strengths and weaknesses, as well as several aspects related to system optimization design principles (Castelli and Mazzetto, 1986 and 1988; Riva et al., 1987). Among these, photovoltaic and wind power systems that exploit solar irradiation and wind speed, respectively.

In line with the need to implement reliable tools to optimize the use of energy and to favour the use of green energy resources in animal farming, the present study pursued the following main **objectives**:

1. To study the energy consumption system in a Mediterranean context and to develop a mathematical model for its optimization;
2. To evaluate the performance of photovoltaic and wind power systems in relation to the environmental conditions in a livestock farm, representative of the study site.

The thesis is divided into four sections. **Section one, “Energy use and production in animal farming”**, provides introductive information on the animal farm classification, work organization and energy consumption and production through the exploitation of renewable energy resources. This section furnishes also general information on the state of the art models and tools developed for energy consumption optimization in other industrial sectors and on the technology supporting the production of green energy. **Section two, “Materials and methods”**, concerns the techniques adopted and methodologies followed to conduct this study, including the selection of a study farm, the detection of energy consumption items, the collection of consumption data and their elaboration to develop and validate a consumption optimization mathematical model, survey of environmental parameters (solar irradiation and wind speed), monitoring of actual energy production by rooftop photovoltaic and wind power systems installed in the study farm. **Section three, “Results”**, shows results and outcomes of the different data collected and their elaboration, including modelling and simulation, which are discussed in the **section four, “Discussion and conclusions”.**

2 ENERGY CONSUMPTION IN ANIMAL FARMING

2.1 Agriculture, farm classification and organization

Agriculture involves crop cultivation and livestock production systems aimed at generating products used to support and improve human life. Both plant cultivation and animal breeding are frequently included within the same farm. Business farm classification is formally based on their prevalent productive orientation and size, with special regard to their turnover. For this purpose gross income standards, calculated on a three year basis, are normally employed for such categorization.

The use of a classification system based on the technical-economical orientation (TEO) is recommended by the European Union. This includes the following three hierarchical levels:

- *general*, each TEO corresponds to a wide productive sector;
- *main*, each TEO is a detail of the general ones;
- *specific*, possible specializations are identified within a main TEO.

On the basis of the proportion of each general and main orientation, a farm is classified according to four different specialization levels that take into account the turnover:

-*specialized orientation,* the turnover associated with a productive activity achieve 2/3 of the whole farm turnover;

-*dual orientation*, the turnover associated with two productive activity is between 1/3 and 2/3 of the whole farm turnover;

-*partially dominant orientation*, the turnover associated with a productive activity is above 1/3 of the whole farm turnover, but not above 2/3;

-*mixed orientation*: no activity exceeds 1/3 of the whole farm turnover (De Gaetano, 2013; Belletti and Marescotti, 2015).

The productive process is represented by all activities involved in the production cycles that need to be managed harmoniously and coherently with the objectives of the entrepreneurs and with efficiency and competitiveness principles.

2.2 Animal farming

Although animal farming can be conducted according to different management techniques, several are the in common aspects that can be identified in any livestock system.

A livestock system can be defined as a pool of state variables (eg. physical environment, animals, production, technical equipment, people, capitals), and functions (flow of energy, material and information), including the relationships existing among all components.

Although it might be difficult to classify livestock systems, it is possible to make a distinction on the basis of the following four criteria:

1) productivity and relationship with the local agricultural system providing animal feed;
2) farm specialization and animal productivity level;
3) internal organization degree;
4) social and economical aspects.

1) <u>Productivity and relationship with the local agricultural system providing animal feed</u>

Animal breeding may totally or partially depend on, or be completely unrelated to animal feed production. In the latter case animal husbandry is defined as no-soil farming.

The farm may include forage crops with different productivity levels, depending on soil fertility, technical and environmental conditions. A useful productivity indicator is represented by the number of animals that can be supported by a farm surface unit, normally expressed as animal weight (kg) / surface (ha), and referred to the average year under ordinary conditions. The farm self-supply index, expressed as energy or dry matter, is calculated as the ratio between the feed annually produced in the animal farm and the whole feed consumption.

2) Farm specialization and animal productivity level

A main distinction can be made between specialized and mixed farms. The first type includes only one animal species (individual orientation), while the second involves more species (mixed orientation).

The productivity level, expressed as a percentage, refers to the position of a specific farm in respect to a reference population of farms.

3) Internal organization degree

Based on the technological level associated with the productive process management, animal farms can be distinguished in farms with a high, average or low technological level. In the first case, an extensive mechanization and computerization of farm operations is observed, which lead to precision livestock farming (Fournel et al., 2017). By contrast, in other cases the use of technology is limited, even if occasionally advanced techniques and equipment are employed.

A critical aspect in livestock farming is the real-time data recording and elaboration procedures, which should provide in time information to the farmer, thus properly supporting the management and decision making process.

4) Social and economical aspects

Animal farms can also be classified in relation to the local social and economical context and the relationships and connections with the National and International market, which define the type of company and its position within the productive context.

Considering the intensity of productive factors use (i.e., soil, work, capital, production process organization), animal husbandry can be classified in four different types. The intensity degree of a farm is represented by the ratio between cost of labour and revenues, that is defined as Labour Cost Index (LCI). On this basis, a livestock system can be intensive, semi-intensive, semi-extensive, and extensive.

1) Intensive.

The farm normally involves a single productive orientation, is highly specialized, with a high productivity and technology level, an LCI between 20 and 30 %, and is based within a mature entrepreneurial environment. This category includes no-soil swine, poultry and rabbit farms, where animals are subjected to permanent housing.

2) Semi-intensive.

The productive factors are employed at a lower level compared to intensive farming, the LCI is between 30 and 40%, and animals breeding is based on semi-permanent housing. This category includes dairy cattle farming involving some grazing, poultry ground breeding, swine *plain air* systems, sheep and got breeding under both housing and grazing conditions.

3) Semi-extensive.

Animal breeding is mixed, the productive level is average-low, the LCI is between 40 and 50%, and grazing is usual. This system includes several sheep farms with a good production of milk and meat, and cattle kept on pasture.

4) Extensive.

The productive orientation is normally mixed, all productive factors are used at minimal level, the number of animals per surface unit is low, animal housing is rare or absent, and pasture is the sole or the prevalent animal feed source. This category includes sheep for wool and meat production, rustic cattle, goats and swine in the wild.

2.3 Use of energy in animal farming

Modern livestock farming has evolved toward a continuous increase in the investment needed to keep abreast of the technology advancements and to face the industrial dependence on feed and energy providers.

The technological progress caused an intense farm renovation, and the livestock sector has been featured by two main trends: ergonomic reorganization toward an increased farm size and mechanization increase.

Consequently, the increased use of more technological equipment translated into an augmented energy consumption, which determines the need to contain the production costs, so as to be competitive in the market.

Most studies on the reduction of the environmental impact in animal farming, are mainly focused on animal feeding techniques and methods, which represents a fundamental energy input in such productive systems (Eriksson et al., 2005).

More in general, it can be stated that the energy need - *in sensu lato* - represents a key factor for profitable animal breeding. In this context it is important to distinguish between the so called "inclusive energy", represented by all farm components (Hammond and Jones, 2008), and the "operating energy", that is the energy input that makes the system work every day. The latter, representing a high cost for the farm, includes the electrical energy needed to maintain an appropriate animal breeding environment.

2.4 Energy consumption optimization

Despite significant differences among livestock production systems in diverse world areas, related to different animal races, climatic conditions, farm operations, and market objectives, the sustainable use of energy represents a common purpose (Lammers et al., 2010; Murgia et al., 2008; Rossi, 2011).

Energy consumption optimization requires the implementation of energy management tools ad hoc designed on specific animal husbandry models, like those typical of the Mediterranean environment (De Corato and Cancellara, 2014). These animal breeding systems, especially if intensive, normally involve the use of highly energy demanding equipment (i.e., lighting, air-conditioning, ventilation, heating), which usually translates into an important electrical energy need.

Reducing this energy consumption would be strategic and beneficial not only to the environment, but also to increase the overall farm productivity with significant money savings.

Several methods and mathematical models to optimize the use of energy have been developed in a variety of industrial sectors (Clarke, 1988; Colon-Vazquez, 2011; Frangopoulos, 2009; Méndez-Piñero and Colón-Vázquez, 2013).

The application of mathematical models for analysis and optimization of energy consumption in animal farming is well documented, however most of the related studies are mainly focused on the animal feed rations and diets (Kelemen et al., 2015).

The development and application of mathematical models aimed at managing and reducing the use of electrical energy (a major factor of production), is less studied. Indeed, electrical energy significantly contributes to the economical farm balance and it should become a main target for the farm managers pursuing cost minimization and profit maximization objectives.

One of the approach to pursue significant middle/long term energy savings is the replacement of the most energy-demanding equipment with less energivorous alternatives. Such purpose is normally achieved through the acquisition of new instruments when old ones are obsolete, or occasionally to exploit specific incentives. Hence, a lack of a proper plan for equipment replacement based on energy consumption optimization in the farm is still very common.

3 ENERGY PRODUCTION FROM RENEWABLE RESOURCES

3.1 Energy resources

Energy sources can be classified as primary or secondary, depending on their availability in nature and if they can be directly used.

Oil, coal, natural gas, biomass, nuclear fuel (mainly uranium) and renewable sources are classified as primary sources, while gasoline, LPG (liquefied petroleum gas), hydrogen and electricity are secondary energy sources, deriving from properly treated primary sources.

Based on another classification criterion, conventional and non-conventional or alternative energy sources can be identified. The first category includes fossil fuels, while all the other sources of energy are defined as alternatives.

Fossil fuels are among the non-renewable energy sources, whose cycle of production and reproduction timing is not comparable with the human consumption timing. Their exploitation undermines their availability on Earth and consequently, their exhaustion timing is strictly dependent on the intensity of their use.

Renewable energy sources are by definition inexhaustible (i.e, wind, sun, water, earth's endogenous heat) or able to reproduce very quickly (i.e., firewood and biomass).

More in general, renewable energy sources are those that the planet provides without changing its energy balance and without affecting existing resources" (Pallabazzer R.,2011)

In the case of solar energy, thermal solar energy is converted directly and instantly into electricity using photovoltaic technology whereby panels from doped-silicon cells, exposed to solar radiation, generate electricity.

In wind power systems, the wind's kinetic energy is converted into electrical energy by converting the mechanical energy generated by the rotation of wind turbine blades.

Hydropower is the power generated by falling water or fast running water. The kinetic energy of the water masses in motion rotates the turbines that transmit their mechanical energy to the alternator for the production of electrical energy.

Geothermal energy is generated by geological heat sources. It is based on the exploitation of the natural heat of the earth due to the thermal energy released by a nuclear decay process of radioactive elements naturally contained within the mantle and crust.

The term biomass refers to organic matter that can be used in special plants to produce energy. Such matter can have varying origins, and includes waste of agriculture, livestock and food industry, animal wastes, municipal waste or even plant species specifically grown for this purpose.

The national legislation defines biomass as “the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, the cuttings and pruning residues from urban green areas as well as the biodegradable fraction of industrial and municipal waste" (CE n. 18/2001)

If biomass is burned produces fossil-free thermal energy, and when fermented inside special digesters, anaerobic processes produces biogas. It can be also used to produce biofuel (eg. biodiesel from rapeseed oil, ethanol or ethyl alcohol from grain and sugar-rich vegetables).

The interest in renewable energy has grown significantly over the last years, especially in response to a predicted fossil fuel depletion and to the concerns associated with global pollution (Chel and Kaushik, 2011).

A further classification of renewable energy sources, based on the level of technological exploitation, discern among classical renewable sources, new renewable energy sources (NRES) and innovative renewable energy sources.

The classical inexhaustible sources are those whose exploitation is based on widely validated and over time consolidated technologies, such as hydropower and geothermal energy.

The new renewable or second-generation renewable sources, which include wind, photovoltaic (solar and thermal) and biomass, are those for which a higher scientific and technological development effort have been made, so as to scale up their use.

Innovative renewable sources, also known as brand-new sources of renewable energy, future renewable or third generation renewable sources, are based on ultra-modern technologies, many of which are still at an early experimental stage. These include the exploitation of solar energy through thermodynamic solar concentration technology and many forms of marine source systems.

Considering the production of electrical energy, all energy sources and especially the renewable ones, can be further classified as programmable and non-programmable sources, depending on whether the energy production can be organized and regulated in relation to use.

The first group, in addition to the non-renewable sources such as fossil and nuclear energy, also includes some renewable sources such as hydroelectric power produced in tank and reservoir plants, and biomass, including the biodegradable fraction of municipal solid waste.

The non-programmable sources include most of the renewable sources like wind, solar, and geothermal power systems.

In summary, the renewable energy sources are those whose use does not affect their availability for future generations. Besides "Renewable Energy", the term "Sustainable Energy" is often used to highlight the concept of sustainable development based on an environmental and social perspective.

3.2 Photovoltaic power system

A photovoltaic power system allows the direct and instantaneous conversion of solar into electric energy through photovoltaic technology.

The main functional components of a photovoltaic system include:

- photovoltaic panels made of semiconductor material;
- photovoltaic inverter to convert continuous into alternating current;
- devices for energy storage (battery);
- electric panels and counters;
- assembly structure.

The elementary component of the photovoltaic system is the photovoltaic cell. More assembled cells are connected to each other to make a photovoltaic module; more modules make a panel; more panel series make a string; more parallel strings are connected to make a photovoltaic generator.

The photovoltaic cells, are generally made of silicon and when exposed to solar radiation are able to generate electricity through the so called photovoltaic effect (Sproul A., 2017). This process occurs when an electron present in a conveniently treated (doped) semiconductor material is hit by a photon.

Silicon is a tetravalent atom, which means that has four outer electrons available for chemical bonding, so that in a crystal of silicon, each silicon atom bonds to four other silicon atoms.

Because of the property of silicon to form a crystal involving all of the bonding electrons, it is called a semiconductor. As a result of heat or light, if a sufficient amount of energy (1.1 electron-volts, corresponding to 1 photon) is supplied to the crystal, covalent bonds can be broken and the electron is free to move throughout the crystal.

In a process called "doping", phosphorus (dopant atom) can replace some of the silicon atoms. Phosphorous is pentavalent and bind covalently to silicon in the crystal involving 4 of his electrons. Consequently, the fifth electron is only weakly (0.045 electron volts bonding energy) attached to the phosphorous atom, and as a result of a slight temperature increase (or just at normal temperature) this electron is free to move throughout the crystal. It can be inferred that the silicon crystal electrical conductivity can be changed by adjusting the number of dopant atoms in the crystal. Because of this free to move electrons from dopant atoms, the resulting crystal material is called n-type silicon.

Another type of substitution in the silicon crystal can be made by boron that has only three electrons available for covalent binding with silicon atoms, which means that the resulting crystal has an electron vacancy or “hole”. Room temperature is sufficient to generate the thermal energy causing the movement of a nearby electron to fill the hole. Consequently a hole movement from atom to atom is generated. This hole moving corresponds to a movement of positive charges. When boron or an atom with similar properties is used as a dopant atom generating mobile holes, the resulting crystal is called p-type silicon.

If one side of silicon is doped with a p-type dopant (i.e., boron) and the other side with an n-type dopant (i.e., phosphorous), a p-n junction is formed. This determines a p-region with an excess of electron holes and an n-region with an electron surplus. In the p-n junction electrons move from the region with higher electron density (n) to the region with lower electrons density (p), thus generating a built-in electric field.

When light shines on a silicon solar cell, which is essentially a large p-n junction, current and voltage are generated. Current will flow from the p-type side to the n-type side (conventional current). If the p-n junction is connected to an external conductor, a close circuit in which the current flows from a greater potential towards a minor potential layer, is created. This flow will continue until the achievement of the electrostatic equilibrium, which determines a positive charge density in the n-region, an excess of negative density in the p-region and an intermediate (halfway) region called depletion region. As a result the built-in current field is created in between the depletion region.

To this end, if sun photons enter for instance the n-region, electron-hole couples are generated in both n- and p-regions. The built-in field allows to separate the exceeding electrons from holes, pushing them toward opposite directions. Once pushed over the depletion region, electrons are not able to come back because obstructed by the field.

When the junction is connected to an external conductor, in the obtained close circuit the electron flow from n to p layers as long as the cell is exposed to light. In that way solar energy is exploited to produce electricity in a direct manner.

The electric current generated by the photovoltaic cell, depends both on the size of the surface exposed to solar radiation and on it slope. The main factors affecting electric energy produced by a photovoltaic system are radiation, modules temperature and shadows.

Energy transfer from the photovoltaic system to the user occurs through special devices called inverters, that are DC/AC converters able to transform direct current produced by photovoltaic modules into alternating current for users. In relation to the presence or the lack of a connection to the National electric network (electricity grid), the photovoltaic system can be classified as grid-connected, stand-alone and storage.

Grid-connected

Grid-connected systems are permanently connected to the utility grid through a bi-directional interaction, so that the grid-connected photovoltaic system supplies the excess power, beyond consumption, to the utility grid. These systems do not include an integrated battery solution for energy storage. Several studies on their profitability have been conducted (Colmenar-Santos et al., 2012).

Stand Alone

The power systems are independent and not connected to the utility grid, therefore they are particularly useful to electrically isolated users. This system, in addition to photovoltaic panels and the inverter, includes an integrated battery solution for energy storage, a control unit to optimize energy production, and a charge regulator for stabilization and management of collected energy in relation to the energy consumption needs.

Storage.

It is a hybrid photovoltaic system which combines the two previous system types. It represents an innovative system in which energy production is used in different ways and timing.

In a first phase energy is consumed by users to satisfy their needs and later is stored in batteries that can be filled to capacity. Finally, the excess energy is supplied to the utility grid.

The amount of electrical energy that can be generated by a photovoltaic power system depends on several factors including the environmental conditions of the site in which is installed, the season considered, the size, orientation and slope of the surface exposed to the sun light.

The nominal peak power (kWp) represents the electric power generated by a photovoltaic system under standard conditions (STC):

- solar irradiation perpendicular to the panels = 1 kW/m^2;
- cell temperature = 25°C;
- air mass (AM) = 1.5.

Main advantages of the photovoltaic power system include:

- free and unlimited energy source;
- no polluting substance emission;
- no thermal and noise pollution;
- contribution to reduce the use of fossil fuels;
- easy and fast installation;
- modularity allows to easily increase surfaces based on different needs;
- high reliability and 25 years warranty;
- installation is possible either in urban and in isolated areas;
- easy integration with buildings (eg. rooftops);
- limited maintenance costs;
- reduced loss due to voltage load fluctuations normally associated with energy transfer.

The main limitations of the photovoltaic system includes the still limited production efficiency, the daily and seasonal solar radiation variability, and the sometimes high visual impact of these systems. Their good performance in the Mediterranean environment, including Sardinia (Italy), is well documented (Ghiani et al., 2013; Spertino et al., 2013; Zappavigna, 2011).

3.3 Wind power system

The wind's kinetic energy is converted into electrical power by a wind turbine that can have a vertical or horizontal axis. While small turbines are used for a variety of applications (boats, caravans, traffic signs, battery charging), larger turbines can provide the energy needed at domestic level or in a farm (Manwell et al., 2012).

The power may also supply the electrical grid and be sold to the utility supplier.

Conventional horizontal axis turbines (HAWT) usually include the following main components (Gasch and Twele, 2012):

- The rotor, typically with three white coloured blades (20-40 m in length) pointed into the wind by computer-controlled motors for converting wind energy to low speed rotational energy (10-22 revolutions per minute);
- The generator, consisting of an electrical generator, the electronic control panel, and possibly a gearbox, adjustable-speed drive or continuously variable transmission;
- The tower (60-90 m tall) and the rotor yaw mechanism that give structural support.

Based on their power (Caffarelli et al., 2009), aerogenerators are classified as:

- *micro-turbines:* power is below 20 kW; mainly for domestic use;
- *mini-turbine:* power is between 20 and 200 kW; used to produce and sell electrical energy;
- *turbine:* power is higher than 200 kW; typical of wind farms.

To start producing electrical energy, an aerogenerator needs a minimal wind speed (cut-in) of 3-5 m/s, while project power is normally achieved at 12-14 m/s that represent the "nominal speed". A maximum wind speed (cut-off) around 25 m/s represents the level that determines the activation of a breaking system for safety reasons.

Main advantage of wind power systems include:

- free and clean energy source;
- electricity can be directly supplied to the utility grid;
- fast installation timing.

Main limits of wind power systems include:

- wind variability and unpredictability;
- an aerogenerator needs a minimal wind velocity of 3-5 m/s, and a good working condition is not achieved until speed reaches 12-14 m/s. If it is too windy, the safety system activate brakes (above 20-25 m/s);
- a wind power system require the availability of a significant soil surface that cannot be diversely employed in a farm;
- turbines have a significant environmental impact;
- they imply a significant noise pollution;
- blade rotation may disturb birds.

3.4 Green energy potential in animal farming

Animal farming in the Mediterranean area is often conducted in farms with a mixed orientation, often associated with the availability of uncultivated soils, which can be translated into the availability of space to host renewable energy power systems. Furthermore, photovoltaic solar systems can be placed on rooftops.

The implementation of these systems is favoured by current incentive measures providing financial support to the farmer. For this reason an increase of renewable energy use in animal farming is being experienced in the Mediterranean area.

Although the dependence from climatic factors represents the main limitation associated with these energy sources, the over time variability and seasonality of their availability can be overcome through the combined use of more renewable energy resources. In this way, the individual fluctuation during the day and throughout the year of one resource can be compensated by another (Zhou et al. 2010).

Consequently, copious efforts are being devoted to studying the combination of diverse green energy types, which may lead to the development of hybrid systems. This approach would be significantly beneficial also to the livestock farming context, where extended farm areas can easily host photovoltaic and wind power systems, in harmony with the available natural resources (Bazen and Brown, 2009; Bardi et al., 2013; Dihrab and Sopian, 2010; Qin et al., 2013).

On the other side, a combined or hybrid energy power system may require more complex management work, considering the increased number of variables affecting the optimization of technical and economical objectives. Especially, in these case the availability of optimization tools supporting decision making and farm management is recommended.

Several scientific studies involving the combination of diverse green energy sources, like photovoltaic and wind power systems, have been conducted by different research groups (Dalwadi et al. 2012; Yang et al. 2008; Borges et al., 2010). In the case of hybrid systems, most studies focused on their technical reliability, size and configuration optimization (Zhou et al. 2010), interaction performance, technical and economical analyses. For instance, a research group (Tina et al. 2006) developed a mathematical model to estimate and predict the performance of wind-solar hybrid systems in the long term, involving two application types known as stand-alone and grid-connected.

More in general, such studies regard researches conducted on combined systems applied to cities (Dalwadi e Mehta, 2012), shopping centres (Elhadidy e Shaahid, 2004), small residences (Bakos e Tsagas, 2003), telecommunications stations on remote islands (Yang et al.2008), greenhouses (Mahmoudi et al 2008) or water desalination plants (Kershman et al. 2005).

Though the growing interest on these subjects, there is a general lack o specific studies on the performance of combined solar and wind power systems in animal farming.

MATERIALS AND METHODS

4 STUDY FARM

4.1 Environmental context and general technical features

To collect and analyse the experimental data, a representative animal farm within the study area was selected. The farm is located in Northern Sardinia (Sassari province) and can be identified on the map using the I.G.M. (Military Geographic Institute) sheet No. 460 section IV (Fig. 4.1).

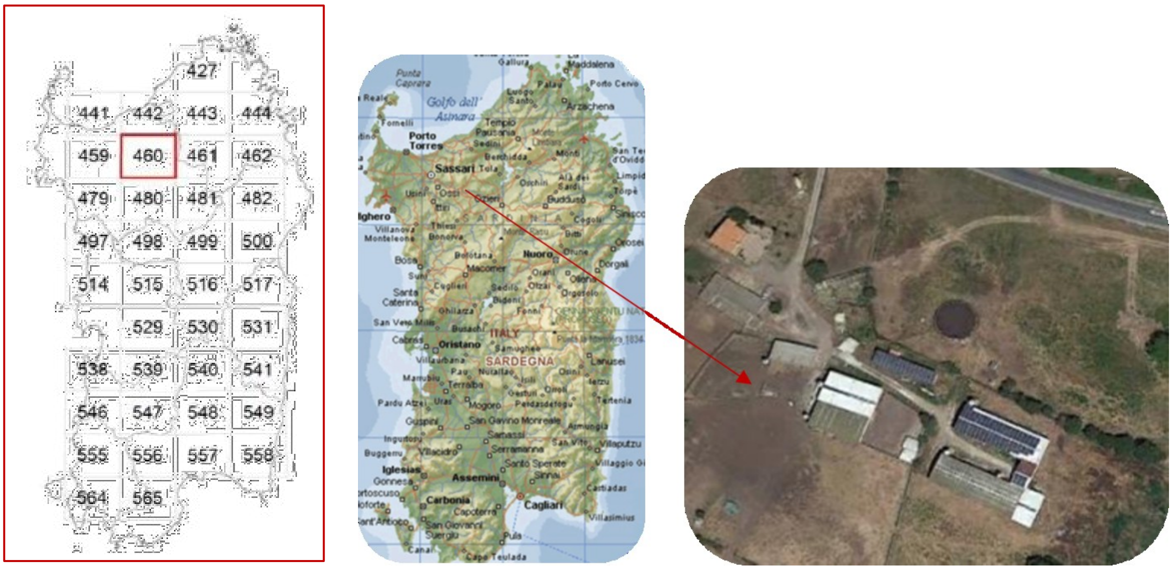


Fig. 4.1 – Map of Sardinia showing the farm location

This livestock farm has a total surface of 44 ha and consists of three main bodies including the following operating centres:

- a pigpen, with a covered area of 785 m^2

- a swine weaning space of 201 m^2

- a pig isolation facility of 251 m^2

- an ovine milking room of 130 m^2

- a farming house of 127 m^2

- an electrical generator place of 9 m^2

- a prefabricated water tank with a capacity of 10 m^3 and a surface of 6.25 m^2

- a sewage sludge tank made of concrete with a volume of 500 m^3.

This farm was selected because of its higher qualitative standard, in terms of technological efficiency and productivity, within the local context.

The area in which the farm is located is part of a geographical and historical region known as *Logudoro*.

The land is partly flat and partly sloping, with a slope rarely exceeding 10%. The altitude ranges between 350 and 370 m a.s.l.

The geological under-layer consists of acid effusive Cenozoic rock. The soil includes a top a 80 cm deep vegetal layer, and is clay, sub-acid with an average potassium and nitrogen content, and a lack of phosphorous.

Stoniness, expressed as the percentage of particles with a diameter exceeding 5 cm, is around 10%, whereas superficial rockiness is limited and do not hinder mechanical tillage.

4.2 Internal organization and production cycles

The study farm is characterized by a dual productive aptitude: ovine and swine.

Animal breeding system is semi-extensive for sheep that are maintained to pasture and occasionally in shelters, and intensive for pigs that are involved in a closed-cycle fully conducted in the farm.

Livestock includes 90 productive sows and 250 sheep. The animal races are the Hybrid English for swine and the Sardinian for ovine.

Intensive swine breeding is conducted in different settings, each characterized by a specific phase of the reproductive cycle:

- Reproduction area: fecundation, gestation, delivery room, weaning;
- Fattening area: including different pig growth levels.

The production cycle is based on a regular 21-day cycle, with synchronized pregnancies. Young sows (gilts) of 5-6 month age are in heat every 21 days, and after being fecundated, become sows which have a 114 day gestation period, corresponding to 3 months, 3 weeks, and 3 days (Fig. 4.2).

The farm normally sells living pigs, with most of the production being represented by traditional 7 kg piglets. Suckling (25-35 kg), young (100 kg) and fat (150 kg) pigs are also sold.

Fig. 4.2 -Sow with piglets

The ovine breeding produces milk, wool and meat (lambs, sheep and rams). The milk is produced over a 227 day milking period, and is totally sold to a cheese producing cooperative. Milking is carried out daily in a milking parlour (Fig. 4.3).

Fig. 4.3 – Sheep milking parlour

5 ENERGY CONSUMPTION SURVEY

5.1 Detection and analysis of equipment involved in the production cycles

An in-depth survey was conducted to identify all the energy consuming instruments and devices involved in farm operations. For this purpose, a detailed investigation was initially focused on the detection of all activities involved in different farm production cycles, thus surveying all equipment, devices, and plants. An appropriate distinction between ovine and swine production cycles was made from the very first visits to the farm. All direct observations and measures were always corroborated by interviews to the farm manager, so as to gather further information on the actual use of each device within a specific production cycle. For each identified consumption item, power (kW) and time of use (h) for relevant devices were recorded. These data were then used to define the typical daily, monthly and annual consumption.

Farm operations were initially gathered into a macro-group representing the whole farm consumption, and later grouped within a specific production cycle. The macro-group included:

1. Pig-shed ventilation;
2. Pig-shed lighting;
3. Pig-shed air conditioning;
4. Lighting (building, milking room, pig-shed, generator);
5. Milking and milk refrigeration;
6. Others.

More in detail, for the swine sector, the following energy consumption items were identified:

1. Feeding;
2. Lighting/Heating;
3. Air conditioning;
4. Ventilation;
5. Sludge spreading;
6. High pressure jet cleaning;
7. Submerged pump operation.

For the ovine sector, the operations implied in energy consumption and considered in this study were:

1. Milking;
2. Milk refrigeration;
3. Water heating;
4. Lighting;
5. High pressure jet cleaning;
6. Submerged pump operation.

5.2 Survey of energy consumption levels during the experimental period.

Experimental farm data were collected during the three-year period 2012/2014.

The aim of this survey was to compare different years and different phases of the production cycle within the same year.

Consumption detection was based on a dual approach:

1) measuring the total monthly consumption in the farm using an energy counter installed in the farm;

2) recording the daily consumption associated with each instrument and device involved in the ovine or swine production cycle.

For this purpose, data were recorded on ad-hoc-prepared field sheets that were regularly filled when visiting the farm during the experimental period. A data file was then produced for each device.

The main information included in the device file were:

- device type;
- production cycle;
- power (kW);
- time of use (h) during the day;
- periods of use during the year.

5.3 Data elaboration and analysis

All collected data were submitted to elaboration in order to calculate the average monthly consumption and the level of consumption associated with each production cycle.

The set of data was then used to elaborate and describe a "typical consumption day", thus defining a load curve. According to this methodology, the energy need was determined for each energy type and consumption period.

All energy consumption items involved in each production cycle were surveyed, recording the daily time of use and its rate of employment all over the year. As a result a table reporting the annual consumption was produced.

The detected consumption items and their power for each production cycle are reported in Tables 5.1 and 5.2.

After determining consumption levels, elaborations have been focused on the definition of a typical day that took into account the average hourly use and the period of use.

A daily energy load curve could in this way be generated including all devices involved in a specific production cycle (ovine or swine). Daily data were used to generate a diagram with the whole average consumption referred to the month or to the year.

Data were generally processed using Microsoft Excel software version 2007, to calculate means and variability measures (i.e., standard deviation and standard error). In addition, data were subjected to one-way analysis of variance (ANOVA), followed by LSD test for means comparison.

Table 5.1 – Consumption items considered for the ovine production cycle.

OVINE CYCLE	
Equipment	**Power (kW)**
Vacuum pump	6.00
Milk refrigerator	3.00
Water heating (Boiler)	1.00
Lighting	0.44
High pressure jet cleaning	1.47
Submerged pump system	2.20

Table 5.2 - Consumption items considered for the swine production cycle.

SWINE CYCLE	
Equipment	**Power (kW)**
Feeding	1.00
Lighting/Heating	0.04 / 0.18
Air conditioning	2.20
Ventilation	0.73
Slurry spreading	14.71
High pressure jet cleaning	2.94 / 1.47
Submerged pump system	2.20

6 CONSUMPTION OPTIMIZATION MODEL

6.1 Algorithm development

The mathematical model was developed pursuing the general objective of identifying the opportunities coming from the replacement of actual with alternative electrical devices involved in the farm production cycle, with special regard to the most energy consuming equipment, so as to achieve a significant energy saving. According to similar models used in different industrial contexts, a payback time of 5 years was considered. This period represents the time within which the return on investment is realized.

Although different instruments and devices employed in animal farming have an average life span around 8-10 years, we followed a more prudential approach considering just 5 year, which takes into account the rapid technology advancements and the system of incentives for purchasing more advances instruments that favour more frequent replacements in the farm.

The main objective of the algorithm was to allow an appropriate selection of "cost-effective" alternative equipment that ensures an equivalent functional efficiency in the production cycle, allowing a reduction in energy consumption and, consequently, in costs for the farm. In addition to maximizing the economical benefits, such replacements would also increase the "green impact" of the farm, following the general principles of environmental sustainability.

The study approach to develop the algorithm included a preliminary review of the cutting edge farm consumption models, previously developed and possibly validated in industrial production contexts that could be assimilated to the production cycles of a livestock farm.

Following this review work, we decided to refer to an adaptation of the model developed for manufacturing industry and recently validated on the semiconductor sector (Méndez-Piñero e Colón-Vázquez, 2013). Following model adaptations, the objective function we employed was based on specific variables and constraints, which defined the range of applicability.

In order to generate a reliable model, this study focused on a survey of energy consumption associated with a single farm production cycle. More specifically, the model was developed and validated taking into account the swine production cycle, that in our case represented the preeminent activity in terms of consumption and revenues for the farm.

In order to verify the compliance of the consumption optimization model with the actual farm situation, this study included a market search aimed at surveying the available devices and technological solutions that could replace the actual farm equipment.

For each potential alternative device, the purchasing cost and the technical features (eg. power, consumption, etc.) were recorded.

In summary, the model developed and presented in this study considered the following *variables* and *general constraints*:

<u>Variables:</u>

- Working days/year;
- Daily working hours for each device;
- Cost of energy received from the provider (ENEL);
- Production cycle considered;
- Working area in the farm;
- Number and type of devices employed in the production cycle;

- Actual energy (consumption associated with actual equipment) ;
- Recommended energy (consumption associated with alternative equipment) ;
- Investment cost to purchase alternative devices;
- Payback time (return on investment time) ;
- Money savings/working day;
- Margin achievable through the replacement of actual with alternative devices.

General constraints:

- The electrical devices involved in the production cycle can be identified with certainty;
- Hour consumption (kWh) for each device involved in the production cycle is known;
- The daily use (h) for each device is known;
- The time of use of each device during the year is known;
- The cost of energy (€/kWh) received from the provider (i.e., ENEL) is known (including possible variations depending on the level of consumption);
- The payback time is a precondition.

6.2 Equipment involved in the model development

The mathematical model development and application, as previously mentioned, was exclusively based on the swine production cycle that impacts substantially on the farm's balance sheet. This approach led to narrow the field of study to a production setting that could be appropriately detailed within the algorithm constraints.

As a result of the energy consumption study, because the overall consumption deriving from lighting/heating, ventilation and air-conditioning represented more than 98% of total consumption associated with the swine production cycle, a further model simplification was applied, including only these major consumption items.

Lighting/Heating

Farm lighting is based on the use of neon light that could be effectively replaced by led light. More specifically, there are 40 neon tubes with a power of 0.04 kW, of which 20 are employed for 5 h/day and the remaining 20 just for 1 h/day.

The selected alternative consists of 40 led tubes with a power of 0.01 kW each, that have the same time (h) of use.

Radiant heating in the delivery room and in the weaning area is obtained through 30 infrared lamps that have a power of 0.175 kW each, and are used 24 h/day. This traditional heating system could be replaced by variable heat lamps whose heat output and consequent consumption are adjusted by a variable voltage controller depending on environmental parameters (i.e., temperature). More in detail, this alternative solution involves the use of 20 lamps with a variable power of 0.100-0.175 kW, associated with a temperature sensor.

Ventilation

The actual ventilation system is based on 16 fan rotors with a 60 cm diameter and a power of 0.74 kW each, that operate 10 h/day all over the year. This on-off system could be improved integrating a variable-frequency drive which allows to achieve 30 % energy savings. The solution proposed includes the introduction of 6 motor drivers.

Air-conditioning

This system, operating in the gestation area, is based on an air conditioner including pad cooling with a power of 2.20 kW that is used 24 h/day. An improvement of this system can be achieved associating an inverter which allows to save around 30% energy.

6.3 Mathematical model development by software

After defining the objective function, the variables associated with the algorithm and all data needed for its application and validation, further development activities were based on the use of two software applications: Lingo 15.0 (Lindo Systems) and Vensim® (Ventana Systems).

6.3.1 Model development with Lingo 15.0

Lingo software is a tool used to build and solve linear, nonlinear, and integer optimization models. A special feature of this software is its ability to solve optimization problems in the presence of constraints represented by equalities and inequalities.

In our case, this tool was employed to solve the problem of energy consumption optimization in the farm, referring to the swine production cycle. Initially, we wrote the program using an appropriate symbolic syntax designed on the mathematical model. At this stage Lingo was interfaced with Microsoft Excel to upload energy consumption data.

The main components of Lingo syntax used were as follows:

- Variables, indicated as names ≤ 32 letters
- Instructions, ended with a semicolon

- The objective function, claimed using the words MIN MAX (blue highlighted) followed by the symbol =
- Comments (green highlighted), started with the symbol !
- LINGO generated files with an extension .LG4

After defining the variables, software operators and functions, the model was gradually implemented. These model components included arithmetic and logic operators following specific priority levels, and the mathematical functions needed to formulate the problem to be solved. The model structure involved decisional variables and constraints, so as to obtain a window including the problem solutions, that was the optimum of the objective function. Within the model, the “Sets section” and “Data section” were defined.

As an output, the software produced a report that was in depth analyzed.

6.3.2 Model development with Vensim®

Vensim is a modelling tool that allows to conceptualize, document, simulate, analyze and optimize a dynamic system model, that in our case is represented by the swine production cycle. More specifically, in the present study "stock and flow" diagrams were used to build a simulation model enriched with actual data collected in the study farm during the three year experimental period.

The general principle followed for the model development involved the connection of *words* by *arrows*, so as to establish connections and mathematical relationships between system variables (Booth and Stermanb, 2000).

After being developed, the model was used for several simulations, which allowed to represent and study more in depth the swine production cycle 'behaviour' in terms of energy consumption, costs, savings and margin achievable through the replacement of actual with alternative and more energy efficient equipment.

The model was built in compliance with software instructions (Vensim, 2007), stepwise as follows:

- basic model building;
- analysis of the model structure using the Analysis tools (Tree Diagrams);
- simulation of the first model draft;
- analysis of model behaviour using the dataset Analysis tools (Graphs and Tables);
- controller simulations for model refinement;
- output generation for model presentation (Analysis tool output);
- generation of graphs and tables.

7 ENVIRONMENTAL DATA SURVEY

7.1 Solar irradiance measure in the study period

The sun is a star in which thermonuclear chain reactions produce a special type of energy called solar radiation. This energy propagates in space symmetrically up to the external side of the Earth's atmosphere, so that the available radiated power decreases with increasing distance from the sun.

The solar irradiance is the instantaneous power per unit area (kW/m^2) received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. The part of radiation that reaches the soil is called direct radiation, whereas the remaining part is called diffuse radiation. Another type is the reflected radiation (*albedo*) that represents the percentage of direct and diffuse radiation that is reflected from the soil or surrounding surfaces.

Irradiance data recorded during the three year-study period 2012/2014 included 34,059 instantaneaus measures repeated every 30 minutes in the experimental survey station of SAR (Regional agro-weather service for Sardinia) and provided by ARPAS (Regional Agency for Environment Protection in Sardinia).

ARPAS is a local agency operating to foster eco-sustainable development in Sardinia and to protect and improve natural and anthropic ecosystem quality. Amongst its duties are included environment monitoring and control, and the technical support to local environmental authorities.

Monitoring is conducted through collection and analysis of environmental data.

ARPAS collects these data systematically, and ensures their recording, validation, elaboration, and dissemination, thus supporting environment protection. On the other side, SAR is responsible for more applied aspects of environment preservation, and operates through a territorial monitoring network involving 53 survey stations distributed in the regional area (Fig. 7.1). Data continuously measured in these stations are automatically and remotely recorded.

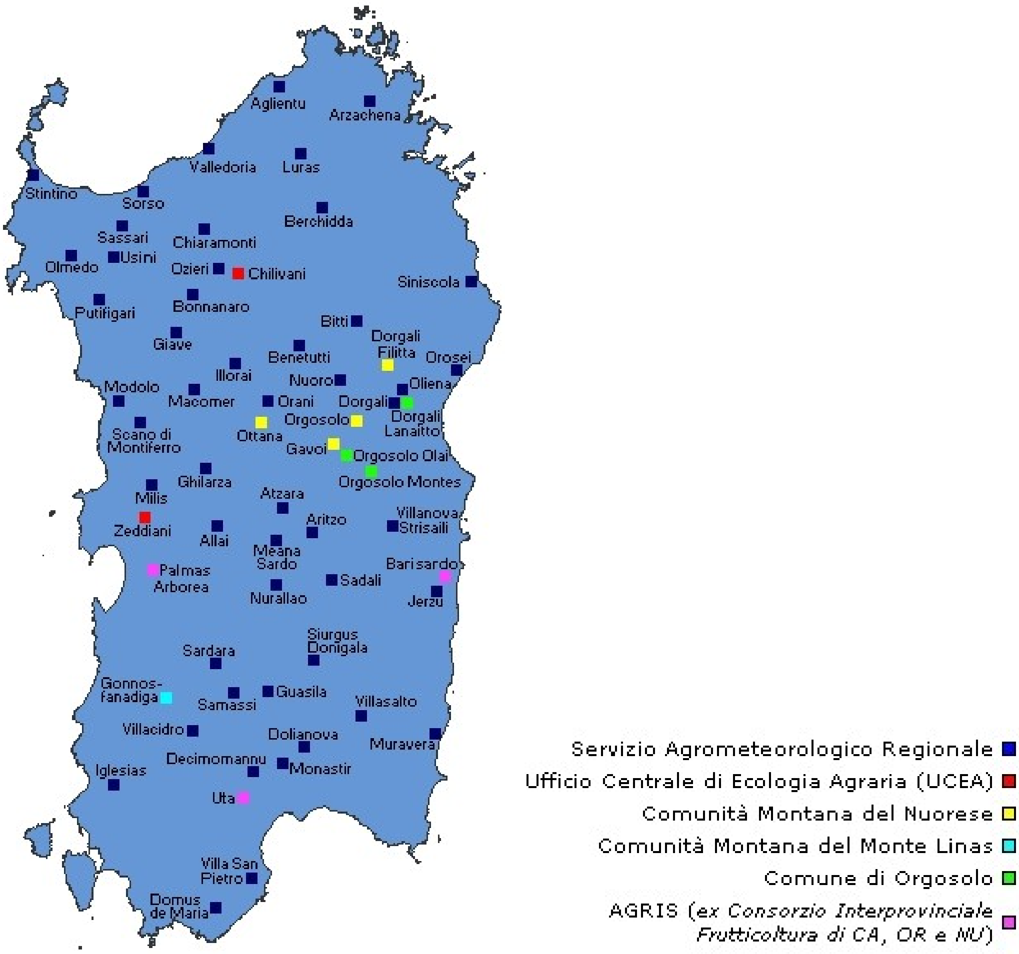


Fig 7.1 - Map of Sardinia with all monitoring stations (*Source: ARPAS*)

SAR uses several Data Banks developed on Oracle relational database, implemented on Unix and Windows platforms including the following:

- station network (*rete stazioni*) database, containing data recorded during the last four months with high time detail;

- historical (*storica*) database, containing data on weather observations from SAR and other bodies like Hydrographic Services, Military Air Force, University of Sassari, Central Office of Agricultural Ecology;

- agro-phenological (*agrofenologica*) database containing agronomic and phenological information on plant development.

7.2 Wind speed measurement during the experimental period

Wind is a vector quantity that has a magnitude and a direction. Wind speed, or wind velocity, is measured as m/s (International System of Units), however there are other traditional units of measurement:

1) knot (nautical miles per hour)
2) km/h.

The knot is used for the measurement of nautical distances; a nautical mile correspond to 1,852 m. Instead, km/h is used to compare velocity measurements of cars or aircrafts.

A traditional scale of measure for wind speed is the Beaufort scale, introduced in 1805 by Francis Beaufort, admiral of the Royal Navy, and modified at a later time.

Boufort scale consists of a level (force), a descriptive term (eg. calm), and a visual description typical for each level.

Table 7.2 shows a comparison among Beaufort force, m/s and knot.

Wind direction is expressed as the direction from which it originates.

Wind speed is measured by anemometer and is conventionally reported at a 10 meters height. It is expressed in degrees (Nord= 0°, East=90°, South=180° West=270°) and is normally averaged over a 10-minute time frame.

Table 7.2 - Beaufort scale, knot and m/s (*Source: Electric Power India*)

WIND Wind Speed at 10 m height	SPEED Beaufort scale	SCALE Wind
0.0-0.4 m/s (0.0-0.9 knots)	0	Calm
0.4-1.8 m/s (0.9-3.5 knots)	1	Light
1.8-3.6 m/s (3.5-7.0 knots)	2	Light
3.6-5.8 m/s (7-11 knots)	3	Light
5.8-8.5 m/s (11-17 knots)	4	Moderate
8.5-11 m/s (17-22 knots)	5	Fresh
11-14 m/s (22-28 knots)	6	Strong
14-17 m/s (28-34 knots)	7	Strong
17-21 m/s (34-41 knots)	8	Gale
21-25 m/s (41-48 knots)	9	Gale
25-29 m/s (48-56 knots)	10	Strong Gale
29-34 m/s (56-65 knots)	11	
>34 m/s (>65 knots)	12	Hurricane

7.3 Data elaboration and analysis

Analysis of data from the SAR station nearby the experimental site, allowed to study the solar irradiation intensity using instantaneous data collected every 30 minutes during the three-year survey period (2012-2014). In total 34,059 instantaneous data were processed for the analysis of irradiation.

Wind speed during the same period was instead studied elaborating instantaneous data recorded in the same SAR station by anemometer with a 10 minute frequency. In total 148,681 instantaneous data were employed in wind velocity analysis.

Alla data were elaborated with Microsoft Excel and mean values (± S.E.) are presented in the result section. Data were submitted to one-way analysis of variance (ANOVA) followed by LSD test for post-hoc comparison of means.

Fig. 7.3 – Survey station of SAR (*Source: SAR*)

Table. 7.3 – List of sensors available in the survey station

Variable	**Sensor height**	**Unit of measurement**	**Minimal available interval**
Wind speed	2 m	m/s	10 min
Wind speed	10 m	m/s	10 min
Wind direction	10 m	°	10 min
Solar Irradiation	2 m	W/m^2, MJ/m^2	30 min
Sunshine	2 m	min	30 min

8 ENERGY PRODUCTION BY THE PHOTOVOLTAIC SYSTEM

8.1 Photovoltaic system

The study farm hosts a photovoltaic system implemented leveraging the regional incentive program supporting the use of green energy in agriculture and animal farming. More specifically, the farm received co-funding for its project after applying to a call within the context of Measure 121 **“**Modernisation of agricultural holdings” (Fig. 8.1).

Fig. 8.1 – Representation of institutions involved in Measure 121.

The purpose of this measure was ‘*to support farm investment and to assist agricultural holdings to improve their economic performance through better use of the production factors including the introduction of new technologies and innovation, targeting quality, organic products and on farm diversification, including non-food sectors and energy crops as well as improving the environmental, occupational safety, hygiene and animal welfare status of agricultural holdings. Furthermore, this measure is also intended to facilitate investments that are made in order to comply with newly introduced Community standards*’. (*Source: Sardinia Region*).

Leveraging this regional support, a rooftop integrated photovoltaic system with a power of 19.98 kW was installed in the farm. Planning and building activities were conducted before the experimental period 2012-2014, and involved several project phases and authorization procedures. Main planning and technical features of the rooftop are presented in Fig. 8.2 and 8.3.

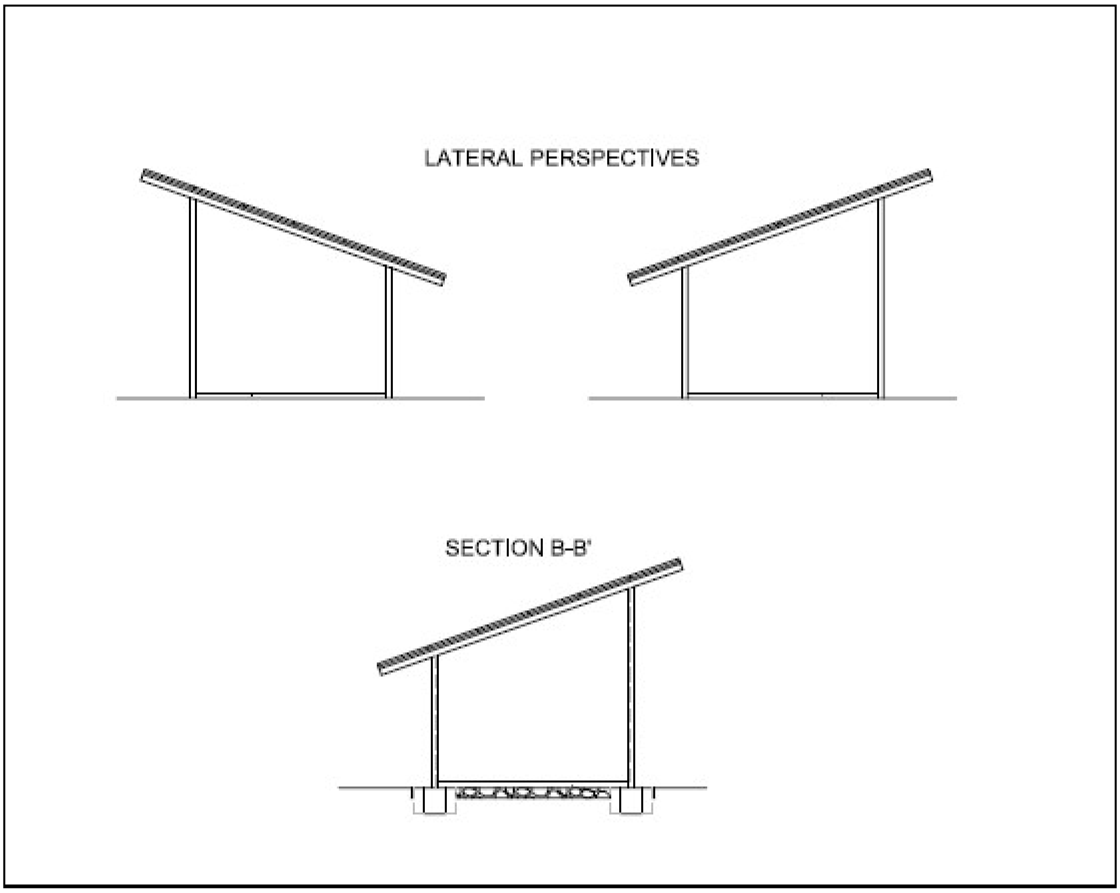


Fig. 8.2 – Lateral perspectives of the photovoltaic rooftop

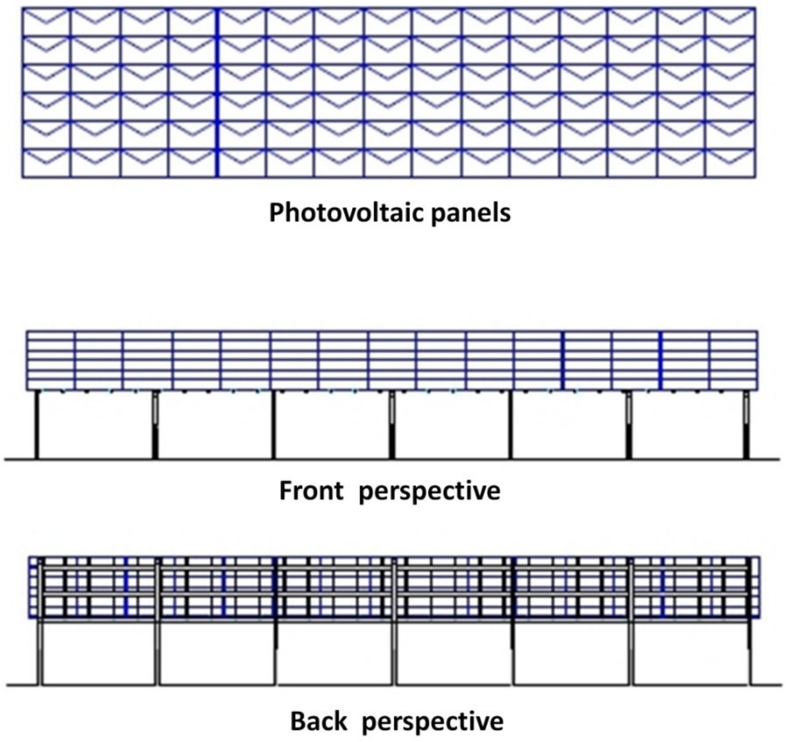


Fig. 8.3 – Perspective drawing of the photovoltaic rooftop

This grid-connected photovoltaic power system (19.98 kW), covering a 150.54 m^2 area, consists of 93 solar panels (Renergies- REN 220/ P 215), 6 inverters (SMA SUNNY BOY 3300 TL HC-IT), a power conditioning unit and a grid connection equipment (Fig. 8.4).

On the basis of a bidirectional interaction, the grid-connected photovoltaic system supplies the excess power, beyond consumption in the farm by the connected load, to the utility grid. Such excess power is sold to the energy provider (ENEL) according to a special tariff (*Second Energy Account for Photovoltaic Ministerial decree DM 19/02/07*).

Fig. 8.4 – Rooftop photovoltaic system

8.2 Energy production during the study period

Photovoltaic energy production during the three-year experimental period (2012-2014) was measured monthly by a dedicated energy counter supplied by the energy service provider (GSE).

GSE is in charge of monitoring and recording the energy (kWh) produced by the photovoltaic system, distinguishing between the energy used for consumption and the energy excess sold to the provider. In other words, a specific “energy account” (Conto energia) with energy “income and expenses” is maintained. This energy exchange concept is in line with the over time varying energy need in the farm and the non-constant environmental conditions that determine a variable photovoltaic energy production throughout the year.

According to the GSE mechanism, the farmer obtains a compensation based on the difference between the economical value of the grid-connected energy produced and the theoretical value associated with the electrical energy consumed in a different period in respect to when it was produced. GSE manages such energy exchange program and pays excess energy through the "Exchange account" (*conto scambio, CS*), so as to ensure a refund (*ristoro*) to the consumer for energy use from the grid. These payments are calculated by GSE taking into account the technical features of the photovoltaic power system and the theoretical and standard user's consumption profile.

8.3 Data elaboration and analysis

Experimental data on the energy production of the photovoltaic power system were collected during the three-year study period 2012/2014. These data were used to study the energy production trend during the year and to compare different years. For this purpose, data were elaborated on a spreadsheet to calculate monthly and annual means. Data were also submitted to analysis of variance (ANOVA) followed by LSD test for the post-hoc comparison of means.

In addition to using actual energy production data, several production simulations were conducted employing environmental data (i.e., solar irradiation) and some simulation software.

9 ENERGY PRODUCTION BY THE WIND POWER SYSTEM

9.1 Wind power system (mini-turbine)

The aerogenerator has a horizontal axis with 3 fiberglass variable pitch blades, synchronous alternator with permanent magnets in radial flow (PMSGR) that works with a variable rotation speed and is directly connected to the rotor without the interposition of speed reducers (direct drive), with double full conversion system AC/DC/AC realized within the inverter at the base of the support tower.

The support tower has an height of 25.30 m, the rotor has a diameter of 15.20 m and allows the three blades to sweep an area of 181.37 m^2. The ratio swept area/power is 6.03 m^2/kW.

The variable pitch airfoil profile allows to maximize the Power Coefficient at different wind speeds and rotation, and to contain the noise level below 37 dbA at 35 m distance and wind between 6 and 10 m/s (according to CEI EN 61400-11).

Technical features of the wind turbine are shown in Figg. 9.1, 9.2, 9.3, and 9.4.

The estimated annual electricity production of the mini wind turbine, for installation at 100 m a.s.l., form factor Weibull k = 2 and 18% turbulence, is listed in Table 9.1.

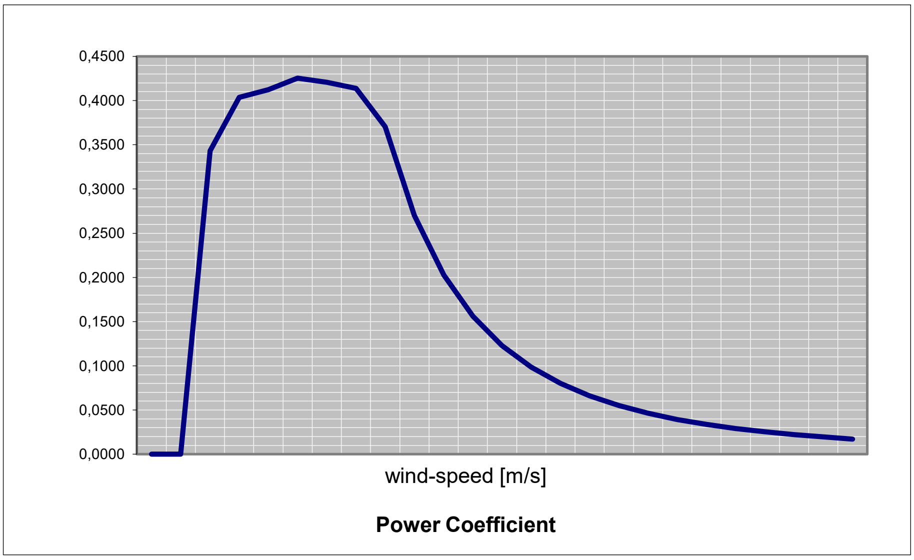


Fig. 9.1 – Wind turbine Power Coefficient curve

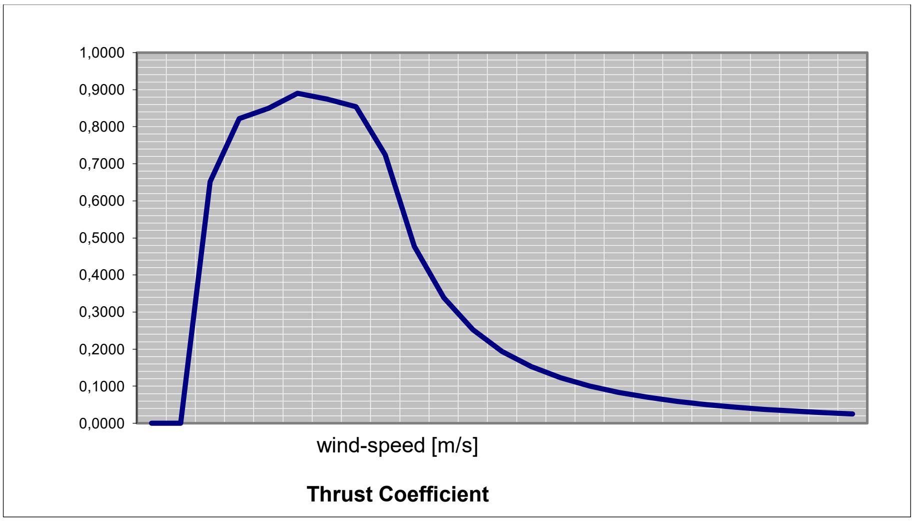


Fig. 9.2 – Curve of the wind turbine Thrust Coefficient

Table 9.1 – Estimated annual energy production in relation to wind speed

Wind speed	Energy production (kWh/year)
4.5 m/s	61,000
5.0 m/s	75,000
5.5 m/s	88,000
6.0 m/s	100,000
6.5 m/s	110,000
7.0 m/s	120,000
7.5 m/s	128,000

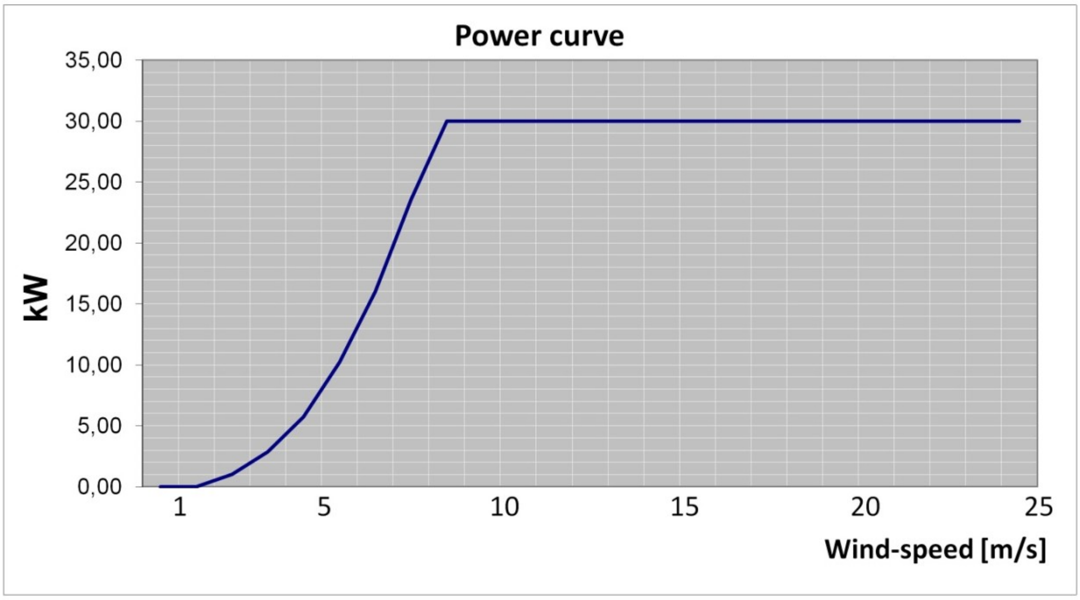


Fig. 9.3 – Power curve of the wind turbin

Fig. 9.4 – Farm aerogenerator (in the foreground)

9.2 Energy production survey in the study period

Energy production was monitored using a specific counting device associated with the wind turbine, equipped with an anemometer and a software continuously recording instantaneous energy production.

Energy production data recorded by this software were downloaded and elaborated in a spreadsheet to calculate average values and the over the year trend. In addition, theoretical energy production levels were determined using the wind speed data measured by the wind turbine associated anemometer and the data provided by the nearby SAR station. These environmental data were used for simulations that took into account the technical features of the wind power plant. For these simulations, the software SimulWind v 5.0, professionally used for planning purposes, was employed. A representation of the dataset used for simulation is shown in figg. 9.5, 9.6, 9.7, 9.8, 9.9, and 9.10.

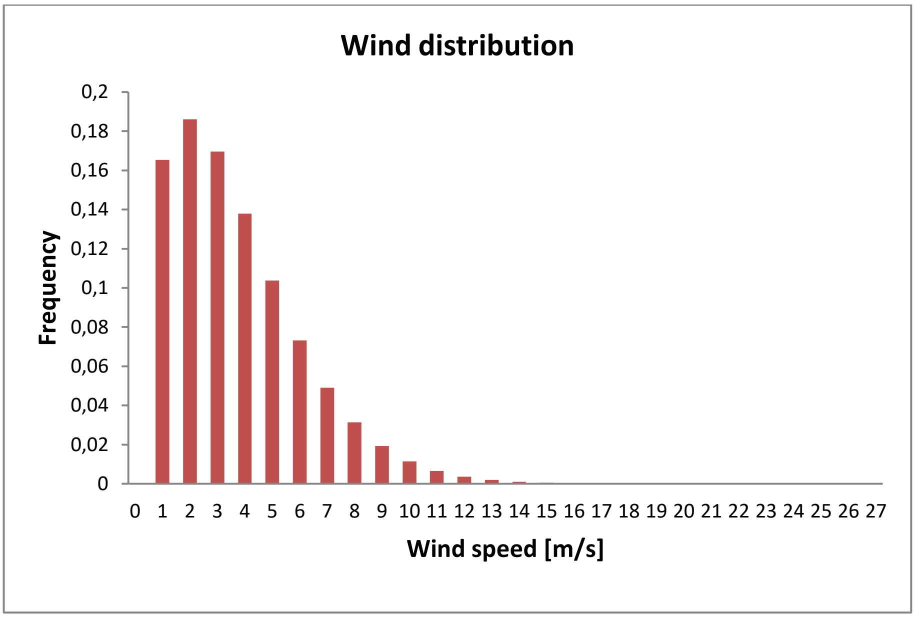


Fig. 9.5 – Simulation of wind distribution in relation to frequency

Emissioni Evitate CO2 [Kg/anno]	*TEP/anno*	*Emissioni Evitate NOx [Kg/anno]*	*Emissioni Evitate SO 2 [Kg/anno]*	*Rimboschimento equivalente [Ha/anno]*
25,461.1	**8.7**	**56.6**	**52.8**	**4.6**
				
636.5	**216.9**	**1.4**	**1.3**	
Emissioni Evitate CO2 25 anni [ton]	*TEP 25 anni*	*Emissioni Evitate NOx 25 anni [ton]*	*Emissioni Evitate SO 2 25 anni [ton]*	

Fig. 9.6 – Evaluation of the avoided environmental impact (*Mancato Impatto Ambientale, MIA*), obtainable using the wind turbine system in comparison with traditional energy sources [CO_2, NO_x, and SO_2 avoided emissions (kg/year and ton/25 years); reforestation equivalent (ha/year)].

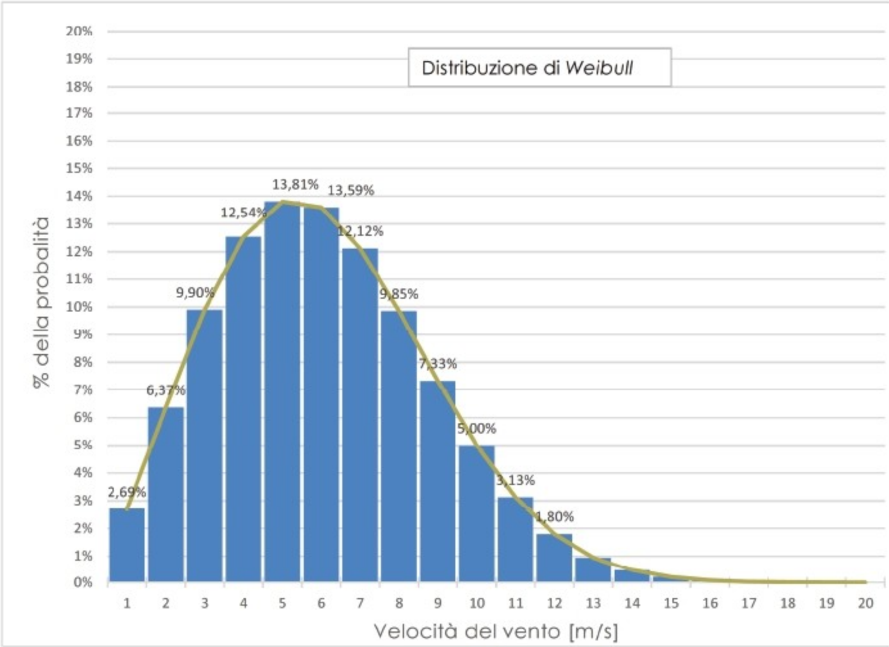
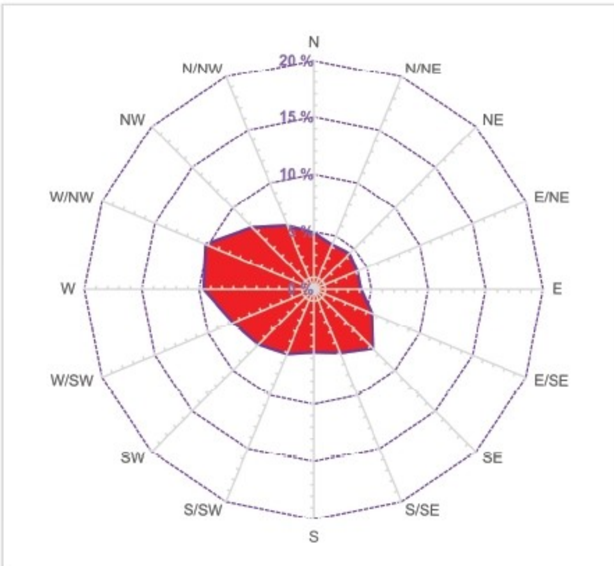
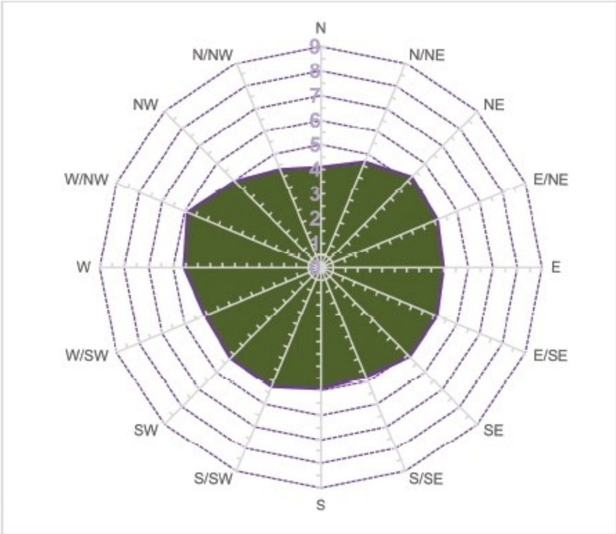


Fig. 9.7 – Probability density function associated with the wind intensity in the installation site



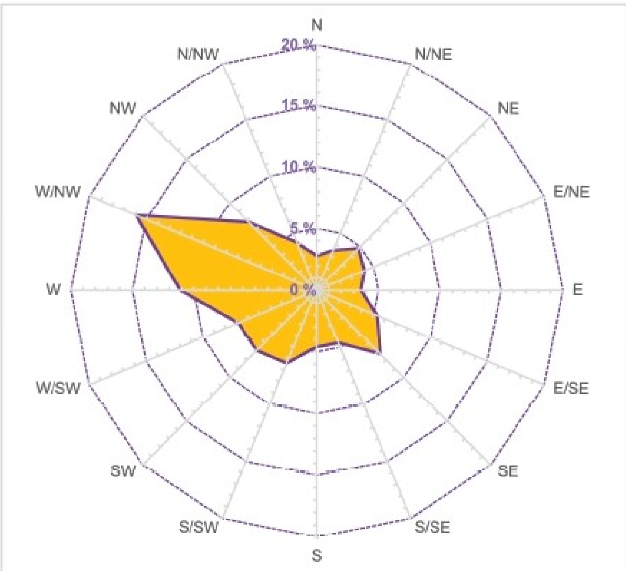
Direzione	%
N	4,9%
N/NE	4,2%
NE	4,4%
E/NE	4,1%
E	4,1%
E/SE	5,5%
SE	7,3%
S/SE	6,0%
S	5,5%
S/SW	6,1%
SW	6,8%
W/SW	7,6%
W	9,6%
W/NW	10,2%
NW	7,6%
N/NW	6,0%

Fig. 9.8 – Wind frequency distribution along the Wind Rose direction in the study site



Direzione	m/s
N	4,09
N/NE	4,66
NE	5,23
E/NE	5,14
E	4,99
E/SE	5,12
SE	5,11
S/SE	4,80
S	4,93
S/SW	5,24
SW	5,19
W/SW	5,09
W	5,57
W/NW	5,88
NW	4,97
N/NW	4,33

Fig. 9.9 **-** Wind velocity frequency distribution along the Wind Rose direction in the study site



Direzione	%
N	2,8%
N/NE	3,5%
NE	4,8%
E/NE	4,2%
E	3,6%
E/SE	5,3%
SE	7,3%
S/SE	4,6%
S	4,6%
S/SW	6,4%
SW	6,9%
W/SW	6,9%
W	11,1%
W/NW	15,9%
NW	7,8%
N/NW	4,2%

Fig. 9.10 **-** Wind power frequency distribution along the Wind Rose direction in the study site

RESULTS

10 ENERGY CONSUMPTION IN THE FARM

10.1. Overall consumption and equipment analysis

Initially, all instruments and devices available in the farm were identified and their usage period for each production cycle was recorded. Consumption was then detected and the typical daily and monthly consumption was calculated for each device and production cycle.

Electrical consumption for each item was expressed in kWh, employing data of the three-year experimental period 2012/2014.

While energy consumption of different pieces of equipment has a general effect on the energy and economical farm balance, the consumption levels have been analyzed and are here presented referring to each production cycle individually: swine and ovine.

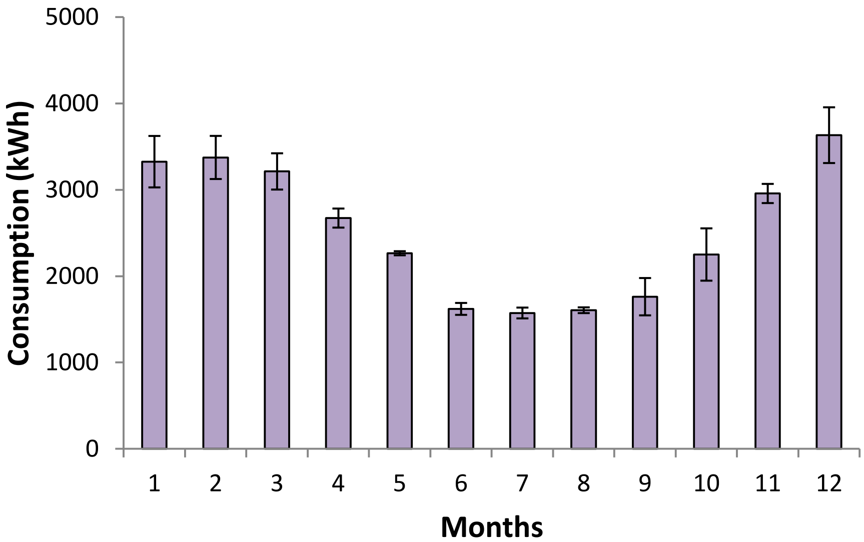


Fig. 10.1 – Total annual energy consumption (mean ± S.E.) in the study farm during the three-year study period

Fig. 10.1 shows the total consumption levels detected in the study period, thus highlighting variations between years and a typical trend featured by significant reductions during summer ($F = 15.15$; $df = 11$; $P < 0.0001$), which corresponds to a minor energy demand from lighting and heating systems.

Daily consumption analysis led to define a "typical day" which represents the averaged hourly distribution of energy consumption and of farm operations during the day. According to this approach, the sum of consumption associated with each item and the relative usage period within a production cycle, allowed to design and study specific energy load curves. After these curves were generated, variations in the energy need in the farm, distinguishing between energy type and usage period, were defined.

In general, energy consumption for each production sector concerned three main usage types:

- Continuous during the year and with daily frequency (eg. animal breeding);
- Seasonal (eg. heating and air conditioning);
- Occasional or at more or less regular intervals.

Farm operations considered in the calculations were grouped as follows:

1 Pigpen ventilation (pig-shed, weaning area, delivery room);

2 Pigpen lighting;

3 Pigpen air conditioning (gestation area)

4 Farm lighting (house, milking parlour, piggery, weaning area, isolation area, delivery room, generator)

5 Milking and refrigeration (vacuum pump., compressor, boiler, refrigerator, washing, pressure washer)

6 Others.

As shown in Fig. 10.2, ventilation in the pigpen (29.19%) represented the item that affected most the whole consumption farm balance, followed by milking and refrigeration consumptions (23.74%), lighting (22.48%) and air conditioning in the pigpen (13.68 %). Minor was the contribution of other energy usage (8.75%).

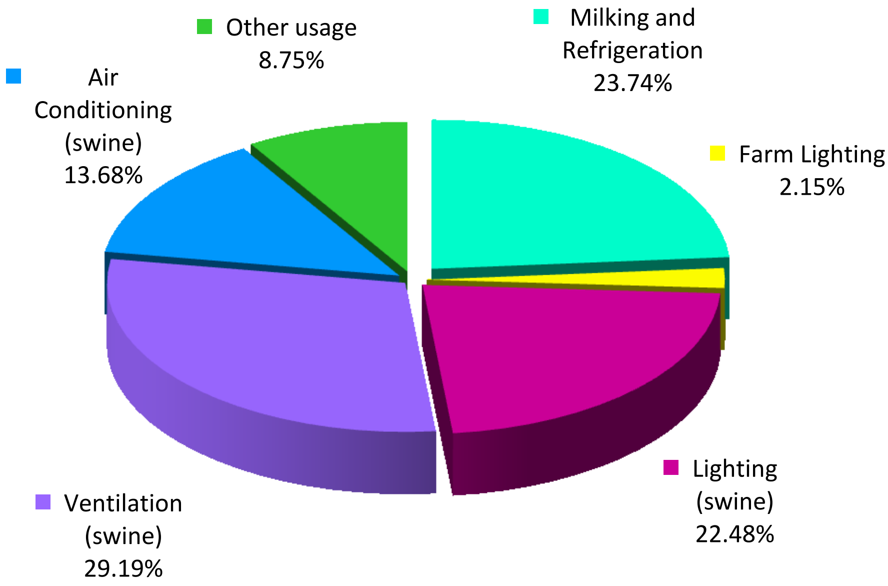


Fig. 10.2 – General farm consumption distribution

10.2 Swine production cycle

Pig breeding in the farm involved different areas where specific activities of the production cycle were carried out. Consequently, each area was characterized by its own energy consumption. In summary, two main areas could be distinguished:

- Reproduction area: fecundation, gestation, delivery room, weaning;
- Fattening area: set of areas that host animals with different levels of growth.

The environmental control in the intensive pigpen is essential for a proper animal growth and to protect them from potential diseases.

Ventilation in such areas is another component needed to create and maintain animal health and wellness (Duncan and Petherick, 1991). In addition, this functionality is required to ensure a sufficiently low humidity level, a proper oxygenation, harmful gases removal, elimination of excess water vapour, and animal heat removal (Brown-Brandl et al., 1998).

In other words, ventilation ensures an optimal air exchange during different seasons of the year:

- in summer it removes the animal produced heat from the breeding environment;
- in winter it contains humidity in breeding areas, avoiding water vapour condensation.

Lighting is needed both for a general animal wellness and to keep warm certain areas, especially the delivery room and the area for weaning pigs.

Heating is obtained through the continuous use of infrared lamps, that are electrical devices emitting infrared radiation, thus producing radiant heating. Several high-power lamps are used.

After considering all devices involved in the swine production cycle, the following seven categories of energy consumption were considered:

1 Feeding

2 Lighting/Heating

3 Air conditioning

4 Ventilation

5 Slurry spreading

6 High-pressure jet cleaning

7 Submerged pump system

1. Feeding. Solid food is distributed once a day through an automatic system of administration including two motors with a power corresponding to 1.00 kW each. This task requires an hour a day and determines an annual energy consumption of 454.00 kWh.

2) Lighting/heating. Essential for animal wellness, it includes lighting of different swine productive areas and infrared lamps (n = 30) for radiant heat in the delivery room and in the weaning area. This item gives an overall contribution to yearly consumption of 31,700.25 kWh.

3) Air conditioning. This is conducted only in the gestation area using and air conditioner with a power of 2.20 kW, which determines an annual consumption of 19,328.91 kWh.

4) Ventilation. Ventilation operates 365 days a year and 10 hours a day. It is needed to create and maintain a suitable environment for animal life and wellness. It is especially required to keep humidity low enough. There are n. 10 fan rotors in the pig-shed, n. 2 in the weaning area, and n. 4 in the delivery room. Each fan rotor has a power of 0.74 kW and the total annual consumption is of 55,839.07 kWh.

5) Slurry spreading. Sewage are collected and distributed in the field as a liquid fertilization every thirty days. This spreading system employs a pump with a power of 14.71 kW, and an irrigation plant consisting of 500 meters Pe pipe and sprinklers. This operation takes on average 3 h and determines an annual consumption of 536.91 kWh.

6) High-pressure jet cleaning. This activity is conducted 12 months a year, an hour per day, using two high-pressure jet cleaners with a power of 2.94 kWp (4h/week) and 1.47 kW (2h/week), respectively, and their use determine an annual consumption of 767.02 kWh.

7) Submerged pump system. The submerged pump has a power of 2.20 kW and a flow rate of around 20 m^3/h. It operates 1 h a day to fill the tank that stores water for all farm usage. This system determines an annual consumption of 402.68 kWh.

As shown in Fig. 10.3, the most energy consuming items in the closed-circuit swine farming are ventilation, lighting/heating, and air conditioning, that count for around 98 % of the total energy consumption in this production cycle. The features of these items are summarized in Table 10.1.

Table 10.1 – Summary of technical features and usage time of the most energy consuming items of the swine cycle

Item	**N. units**	**Power (kW)**	**Usage**	
			h/day	**day/year**
Ventilation (fan rotors)	16	0.74	10	365
Lighting/heating (infrared lamps)	30	0.175	24	365
Air-conditioning	1	2.20	24	365

Finally, being a closed-circuit pigpen, based on a regular 21-day-cycle, energy consumption is homogeneously distributed throughout the year.

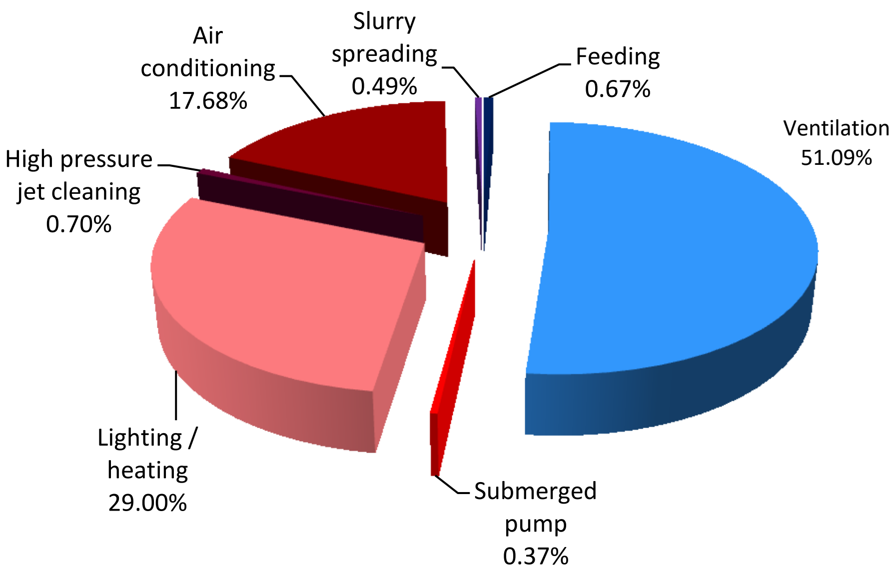


Fig. 10.3 – Energy consumption distribution by category in the swine production cycle

10.3 Sheep production cycle

The most significant energy consumption items in the sheep sector, are represented by mechanical milking and milk refrigeration. The milking plant in the farm, based on the parlour milking concept of positioning the milk line in the middle of the pit above the milker, consists of 24 places and 8 teat cup groups in good conditions.

The following main energy consumption categories have been distinguished within the sheep production cycle as follows:

1 Milking plant (including the vacuum pump);

2 Milk refrigerator;

3 Boiler;

4 Lighting;

5 High pressure jet cleaning;

6 Submerged pump system.

1) Milking plant. The vacuum pump has a power of 6.00 kW and is used twice a day for milking (6:00 a.m. and 17:00 p.m.), in total 227 days a year. It determines an annual mean consumption of 4,086.00 kWh.

2) Milk refrigerator. It has a power of 3.00 kW and includes a cylindrical tank with a nominal capacity of 600 l. It is used 7 h/day and contributes to annual consumption for 4,767.00 kWh.

3) Boiler. It has a power of 1.00 kW, a capacity of 80 l and is used 6 h/day, 227 days/year. Its use determines an average annual consumption of 1,362.00 kWh.

4) Lighting. It refers to lamps placed in the milking room (n. 3 with a power of 0.04 kW, used 6 h/day), necessary to light up the environment during milking. They determine an annual consumption of 163.44 kWh.

5) High pressure jet cleaning. For this purpose a device with a power of 1.47 kW is used twice a week, 227 days/year. It determines an annual consumption of 95.40 kWh.

6) Submerged pump system. This pump has a power of 2.20 kW and a flow rate around 20 m^3/h. It is used 1 h/day to fill a 10 m^3 tank used for all farm activities, 227 days/year. It generates an annual consumption of 500.87 kWh.

Fig. 10.4 shows the contribution of each category to the total energy consumption due to the sheep production cycle. The most energy-consuming items are represented by milking (i.e., vacuum pump) and milk refrigeration, that count for more than 90 % of total consumption.

Because certain activities (i.e., milking) are seasonal, the over the year consumption distribution is characterized by a significant reduction during the dry period (Fig. 10.5).

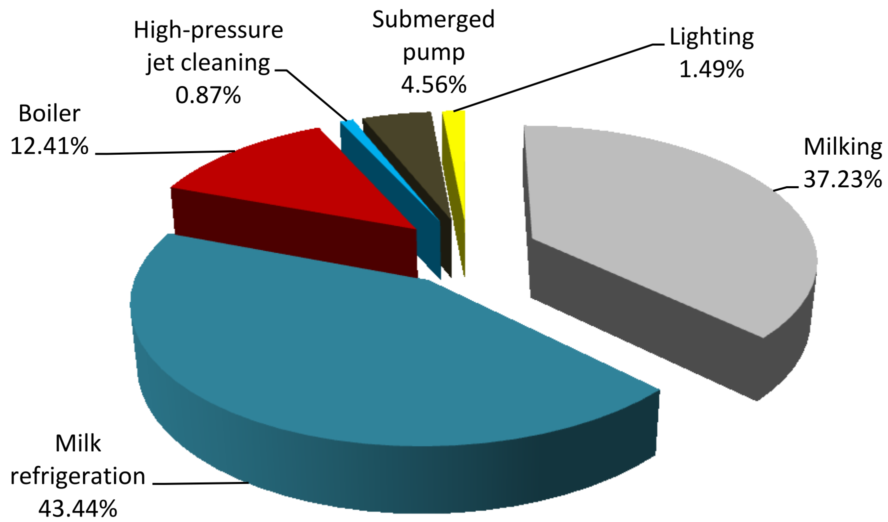


Fig. 10.4 – Energy consumption distribution for the sheep production cycle

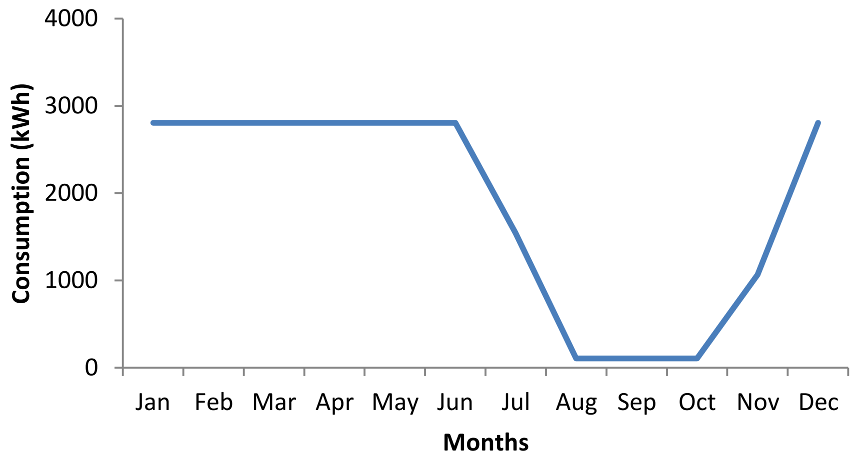


Fig. 10.5 – Annual consumption distribution for the sheep production cycle

10.4 Daily consumption distribution

The consumption analysis during the day, highlighted that specific items are associated with a specific timing during the daily working cycle. More in detail, in the case of the swine production cycle, a peak during the middle day derived from ventilation, while more uniform was the hourly distribution of lighting/heating and air conditioning consumption. Consumption levels for feeding, submerged pump system, high pressure jet cleaning, and slurry spreading are significant during the actual device operation.

Consumption data collected during the three year study period, allowed to describe a "typical consumption day" obtained by averaging hourly and daily data. The consumption distribution during the typical day, mirroring the previously described distribution, is represented in Fig. 10.6. Because the different tasks taking place within the swine cycle are repetitive and continuous throughout the year, the consumption level deviation between a given day and the typical day can be assumed to be minimal. It follows that the distribution shown in Fig. 10.6 is actually representative of the daily scenario.

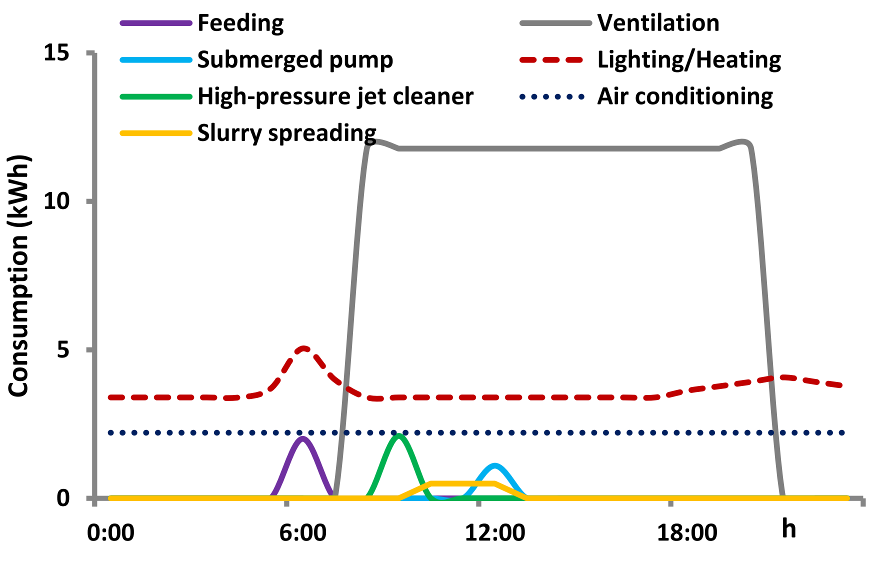


Fig. 10.6 – Typical daily consumption distribution of the swine production cycle

In the case of the sheep production cycle, as shown in Fig. 10.5, the definition of a typical consumption day would be artificial because of milking periodicity, being milking the major consumption item. However, because consumption associated with milking and milk refrigeration represent more than 90 % of total consumption during the lactation period, the typical consumption day gives a reliable representation of the hourly consumption distribution during a day within the lactation period. On the other hand, such distribution is not representative of the dry period.

Fig. 10.7 shows the consumption distribution during the typical day and highlights two peaks corresponding to milking (vacuum pump) operations during the day, followed by two lower peaks relative to the milk refrigeration system.

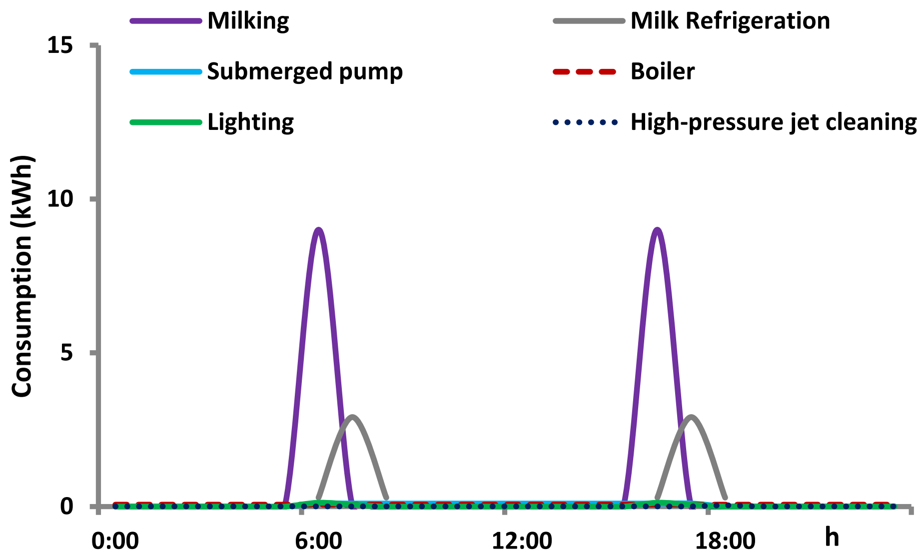


Fig. 10.7 – Typical daily consumption distribution of the sheep production cycle

11 CONSUMPTION OPTIMIZATION MODEL

11.1 Objective function

The previously presented analysis of electrical equipment used in the farm and of their energy consumption, allowed to split out total consumption into different items, referring to a specific production cycle. This approach led to use data from the swine production cycle to develop e predictive mathematical model for consumption optimization and, consequently, energy saving, in the farm. Because energy consumption deriving from ventilation, air conditioning, lighting and heating represented around 98% of total consumption in the swine produciton cycle, these were the sole items considered for the development of the mathematical model.

A first step in this study was the definition of an objective function that would aim at maximizing energy saving, in terms of either energy consumption and the relative cost, through the replacement of actual equipment items with more energy efficient alternatives with equivalent technical performance, and taking into account the required investment cost.

Objective function:

$$max \sum_{(i,j,k)\in\mathbb{N}+} M_{ijk}^{\alpha} \qquad \forall\alpha$$

where

M = margin

i = cycle

j = area

k = device

α = L,V,C

L = lighting/heating

V = ventilation

C = air conditioning

M = Margin, that is the average saving obtained with device replacement, within a specific payback time

$$\boldsymbol{M = Y \cdot P_b \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} S_{ijk}^{\alpha} \cdot x_{ijk}^{\alpha} - \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} C_{ijk}^{\alpha} \cdot x_{ijk}^{\alpha}}$$

where

x_{ijk}^{α} = binary variable $x_{ijk} \in \{0,1\} \; \forall \begin{cases} i = 1 \ldots .n \\ j = 1 \ldots ..m \\ k = 1 \ldots \ldots .p \end{cases}$

Y= year (working days/year)

P_{b} = payback time

S= money saving per working day (€/day)

C= investment cost (€)

S = Saving, that is the money saved through the replacement with alternative devices

$$\boldsymbol{S_{ijk}^{\alpha} = \Delta E_{ijk}^{\alpha} \cdot H_{ijk}^{\alpha} \cdot K_c \cdot P_{ijk}^{\alpha}}$$

where

$\Delta E = E_a - E_r$

E_a= actual energy (consumption in kWh of actual device)

E_r= recommended energy (consumption in kWh with the alternative device)

H=h/day , that is (1/dw) working day (dw = day work)

K_c= cost f energy supplied by operator (ENEL) in €/kWh

P= number of actual devices

Constraint:

$$S_{ijk}^{\alpha} \cdot x_{ijk}^{\alpha} \cdot Y \cdot P_b \geq C_{ijk}^{\alpha} \cdot x_{ijk}^{\alpha}$$

Assumptions:

- 365 working days are considered (dw)
- We consider a 5 year payback time
- Energy cost is based on the local rate (ENEL)
- Device costs are selected on a quality/price basis

11.2 Algorithm development through software

The algorithm was developed employing two alternative software applications: Lingo 15.0 (Lindo Systems) and Vensim® (Ventana Systems).

The first software, Lingo, is able to solve linear, non linear, quadratic, stochastic, and integer optimization models. In our case it was used to solve a specific integer model known as MILP (Mixed-integer linear programming).

Vensim, instead, is normally used for dynamic modelling of complex systems and allows to obtain a conceptual model and the characteristic analysis results at the same time.

11.2.1 Use of Lingo software

A good performance of the model, classified as a Mixed Integer Linear Program (MILP), was obtained with software Lingo 15.0 (Fig. 11.1), which produced a solver status review highlighting the impact of more efficient equipment alternatives in the objective function.

Table 11.1 shows the results deriving from the replacement of actual equipment items with more energy efficient ones. Following the results of software analyses, significant savings are achievable for lighting, ventilation, air-conditioning and heating systems.

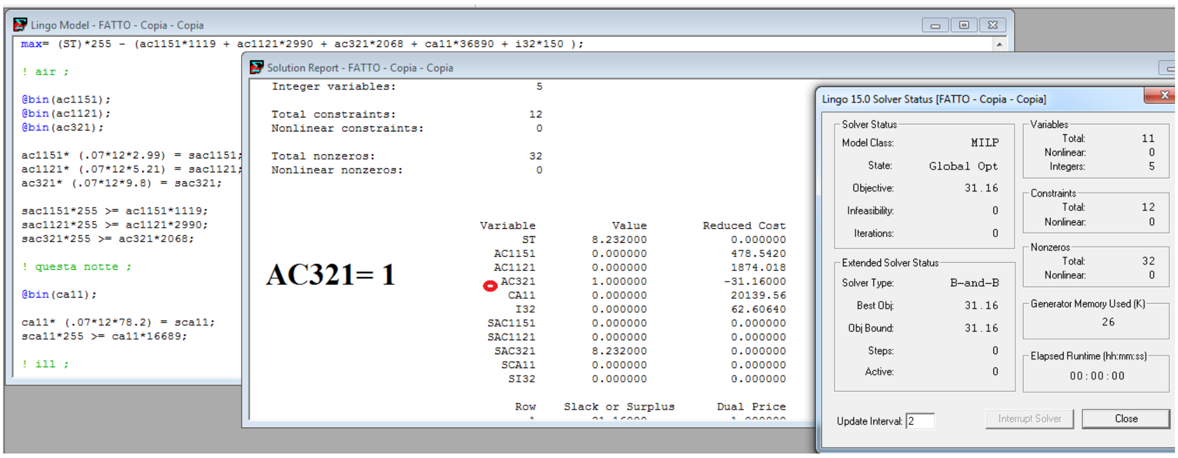


Fig. 11.1 – Representative screenshot showing the output of analyses conducted with Lingo 15.0 software.

More in detail, in the study farm lighting is based on the use of neon light that can be replaced with led light; air-conditioning system including pad cooling can be improved associating an inverter which allows to achieve around 30% energy savings; on-off ventilation system can be similarly improved integrating a variable-frequency drive; heating system relies on traditional heat lamps that can be replaced by variable heat lamps whose heat output and consequent consumption are adjusted by a variable voltage controller depending on environmental parameters (i.e., temperature). The accomplishment of all these savings requires an investment to acquire new equipment, whose amortization cost, calculated for a 5-year period, has been included in annual saving determination. However, the useful life of most equipment is expected to exceed 8-10 years, thus envisioning even higher savings. The investment costs are summarized in Table 11.2.

Table 11.1- Summary of energy cost savings achievable by possible equipment replacement in the swine farm

Equipment	**Consumption (kWh/day)**[a]		**Savings (€)**	
	Actual	**Alternative**	**Daily**	**Annual**[b]
Lighting	4.80	1.20	0.83	262.22
Ventilation	117.68	88.00	6.83	2,071.64
Air-conditioning	52.80	36.96	3.64	729.77
Heating	142.80	112.20	7.04	2,488.87
TOTAL	318.08	238.36	18.34	5,552.50

[a]Daily consumption was obtained adding up energy use levels associated with each hour of the typical day.

[b]Annual savings are reduced by the amortization costs (5-year amortization period) for the necessary investments.

Table 11.2- Summary of the equipment investment needed.

Equipment	Description[a]		Investment (€)
	Actual	Alternative	
Lighting	Neon	Led	200.00
Ventilation	On-off	Variable-frequency	2,100.00
Air-conditioning	Pad cooling	+ Inverter	3,000.00
Heating	Heat lamps	Variable heat lamps	400.00
TOTAL			5,700.00

[a] Details of equipment technical features and consumption levels can be found in the materials and methods section.

11.2.2 Use of Vensim software

Vensim® (Ventana Systems; PLEx32 version) software allowed to develop a dynamic mathematical model employing conventional System Dynamics methods so as to obtain from a complex system, both a conceptual model and a characteristic analysis output.

Model settings involved an Initial Time 0 and a Final Time 1,825 (5 years) using as Units for Time the "day".

The obtained dynamic model includes several "Stocks and Flows" diagrams that simulates the daily economical and energy results, considering a time span of five years, in which we realize the return on investment (Payback Time).

For the most energy consuming items of the production cycle, represented by air conditioning (AC), ventilation (V), lighting (L), and heating (H), individual flowcharts have been created including the following components: two rates, representing Conventional (1) and Alternative (2) Energy Consumption [expressed in kWh/d, and deriving from the product of the variables Hourly Power (kWh)*Use (1/d)], that flow by arrows to the rate "Delta Energy/day" (3) [expressed in kWh/d and representing the energy difference between the actual and the alternative device, being the latter technically equivalent but less energivorous].

The ΔE flow is stored in the variable box Energy Saved (kWh), which represents and encloses the achieved energy saving.

Another stock and flow diagram is generated to represent and define the "Whole Energy Savings"(expressed in kWh), that derive from the flows of rates Energy Savings Total (kWh)*Delta Energy/day* Number Unit (n/n).

All flows converge toward a general system diagram that defines the overall Energy Savings consisting of the rate Whole Energy Savings (kWh) representing the sum of Energy Savings Total obtained from Air Conditioning (AC), Ventilation (V), Lighting (L), and Heating (H).

Once all energy savings have been defined, the last stock and flow diagram is produced to identify the margin (M).

The two rates Money Savings (€/d) and Investment Costs (€/d) flow toward the box Margin (€).

Money Savings are obtained from the product Whole Energy Savings (kWh/d)*Cost of Energy (€/kWh).

Investment Costs (€/d) are instead obtained from the sum of individual Cost Alternative System (€) multiplied by Year (d).

Representative diagrams obtained with Vensim are shown in Figg. 11.2, 11.3, 11.4, 11.5, 11.6, and 11.7.

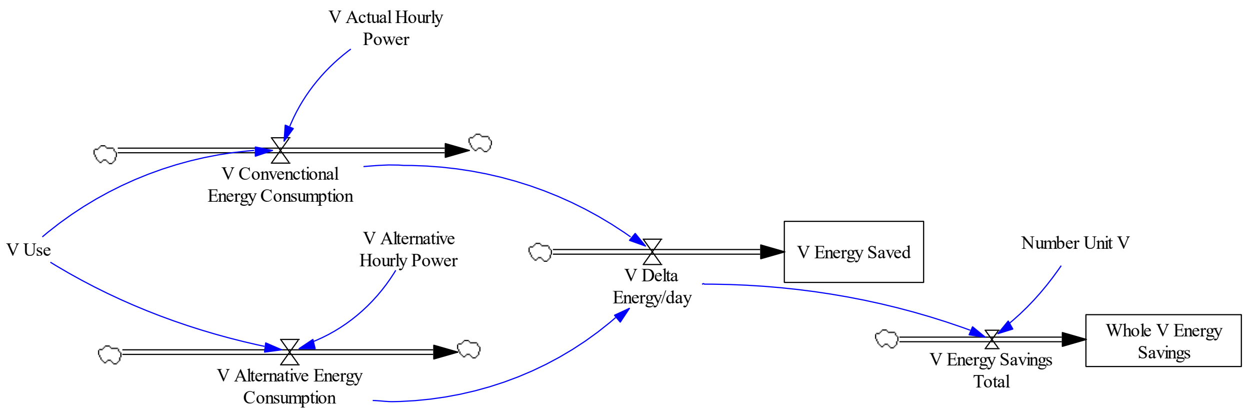


Fig. 11.2 – Stocks and Flows diagram representing Energy Savings obtained through the replacement of the ventilation system (V).

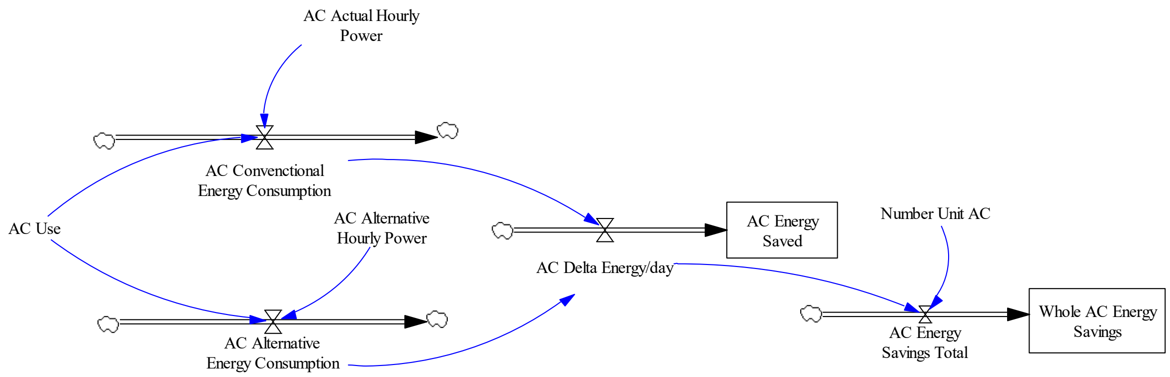


Fig. 11.3 – Stocks and Flows diagram representing Energy Savings obtained through the replacement of the air conditioning system (AC)

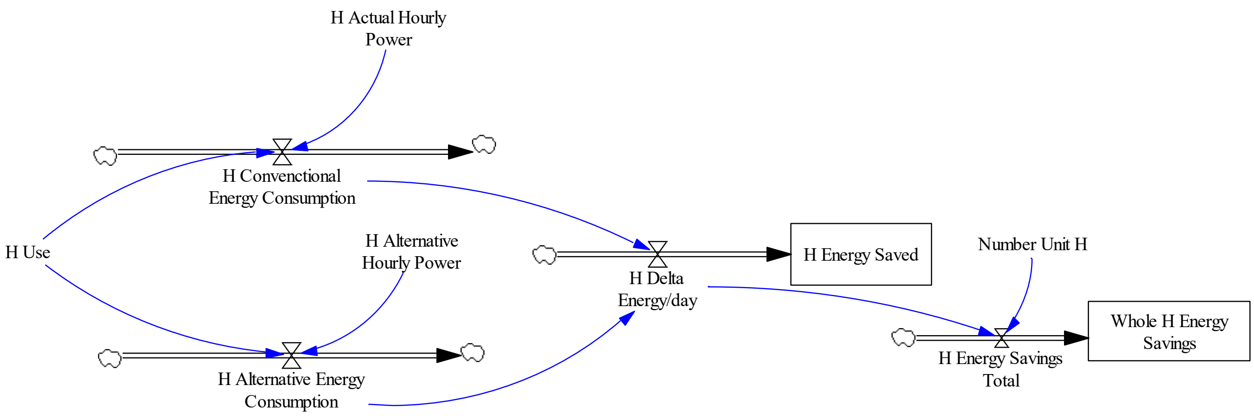


Fig. 11.4 – Stocks and Flows diagram representing Energy Savings obtained through the replacement of the heating system (H)

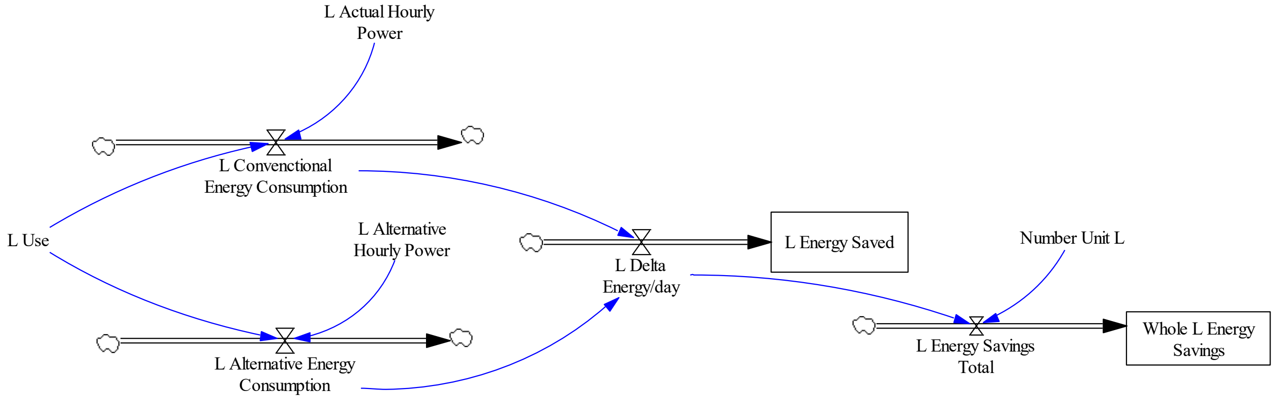


Fig. 11.5 – Stocks and Flows diagram representing Energy Savings obtained through the replacement of the lighting system (L)

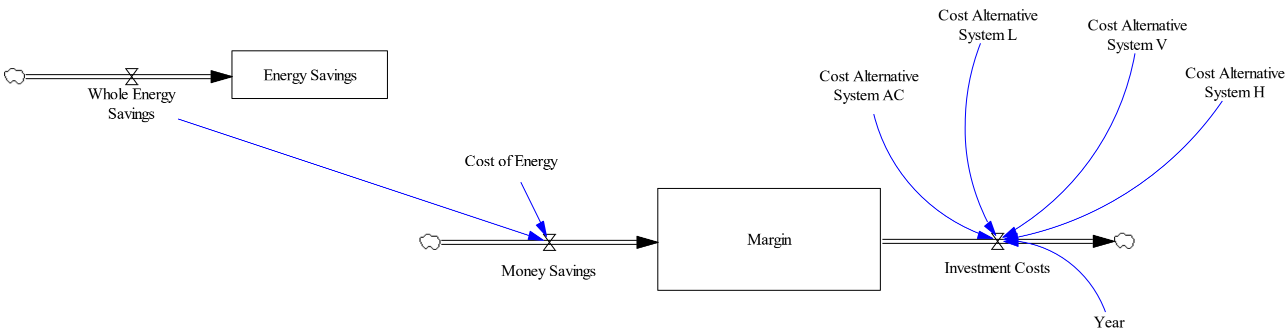


Fig. 11.6 – Stocks and Flows diagram representing the Margin (M) obtained through the replacement of actual with alternative and more energy efficient.

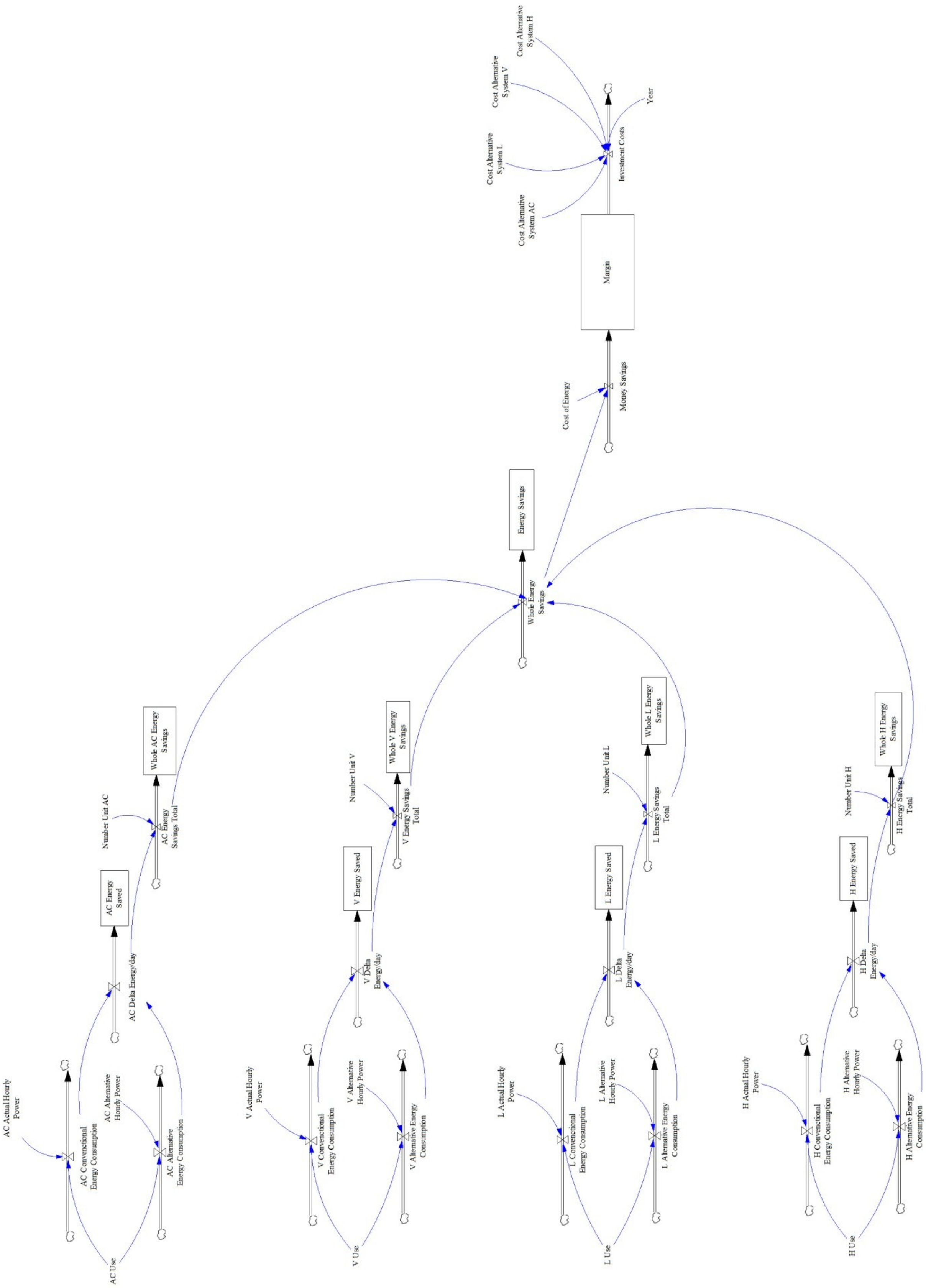


Fig. 11.7 –Stocks and Flows diagram of the whole model developed using Vensim.

The energy saved through the replacement of actual with alternative devices is represented in Fig. 11.8 that shows the achievement of a nearly 145,000 kWh saving after five years for the air conditioning system, followed by heating, lighting and ventilation. The overall savings are greater than 29,000 kWh after 1 year and exceed 145,000 kWh after 5 years.

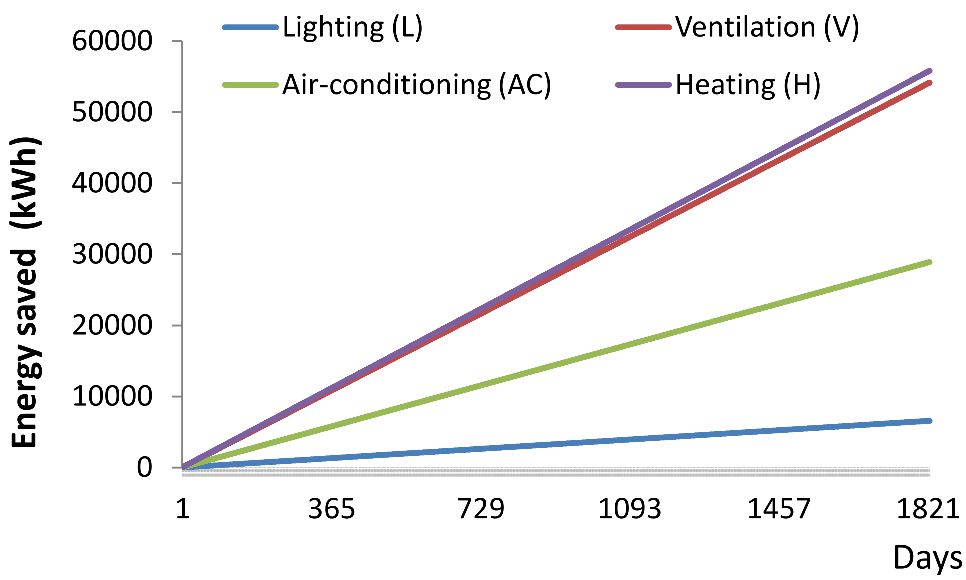


Fig. 11.8 – Energy saving achieved through device replacement.

Fig.11.9 highlights the cause-effect relationship that determines the margin obtained through the replacement of actual with alternative devices. More in detail, the figure includes the Investment Costs that affect in a negative way, and Money Savings that affect in a positive way, the Margin.

Fig. 11.10 shows that implementing this device replacement plan, a positive margin is achieved since the first year. Consequently, the break-even point between investment costs and money savings, corresponding to higher revenues, is reached on the eighth month.

At the end of the fifth year, the total margin exceeds 27,000.00 Euros, with an annual value greater than 5,000.00 Euros.

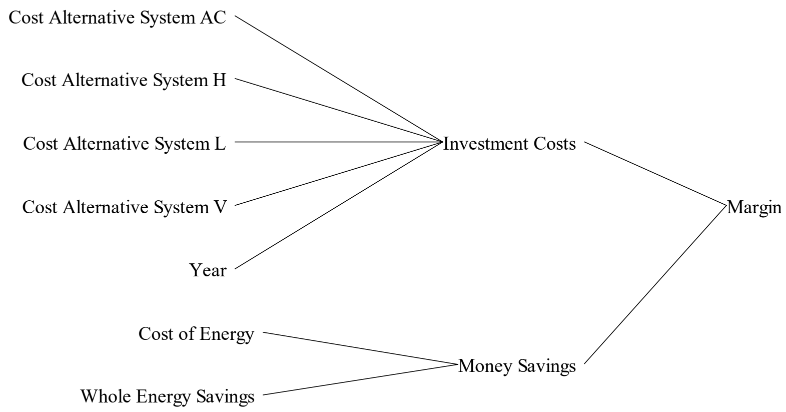


Fig. 11.9 – Cause-tree showing the graphic relationship between parameters determining the Margin.

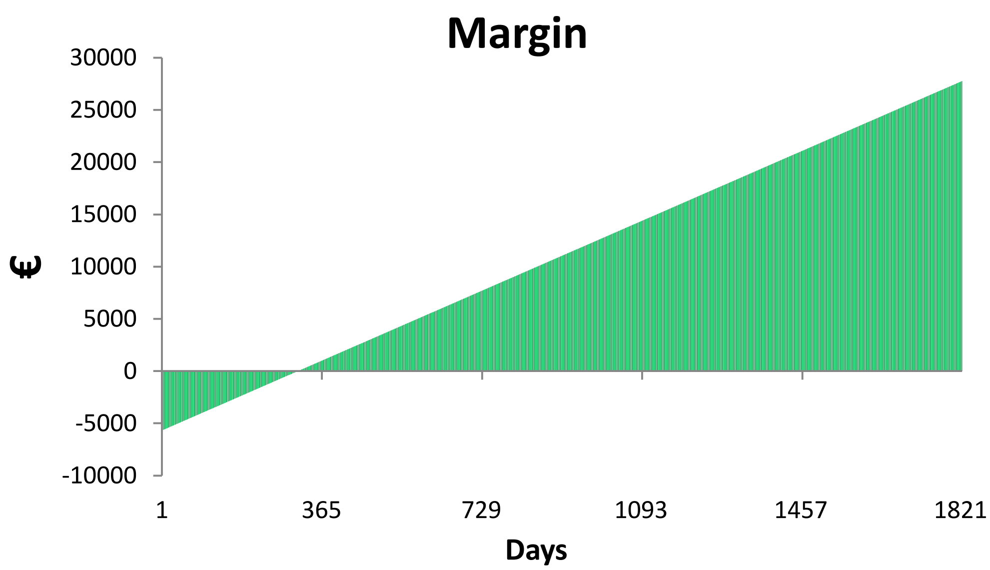


Fig. 11.10 – Graphic representation of the margin achieved in the 5 year payback time through replacement of actual with alternative devices.

12 ENVIRONMENTAL DATA ANALYSIS

12.1 Solar irradiation intensity

Analysis and elaboration of environmental data recorded in the ARPAS station close to the experimental site, allowed to study solar irradiation intensity using instantaneous data collected with a frequency of 30 minutes during the three year period 2012-2014.

In total 34,059 instantaneous data have been used for elaboration. The annual trend featured by peaks in different months is shown in fig 12.1. The average monthly intensity levels are instead represented in fig. 12.2. Analysis of varaiance (ANOVA), followed by post-hoc comparison of means, showed that the annual trend is typically characterized by significantly increased solar irradiation intensity levels during spring and summer ($F = 9.90$; $df = 11$; $P = 0.0016$).

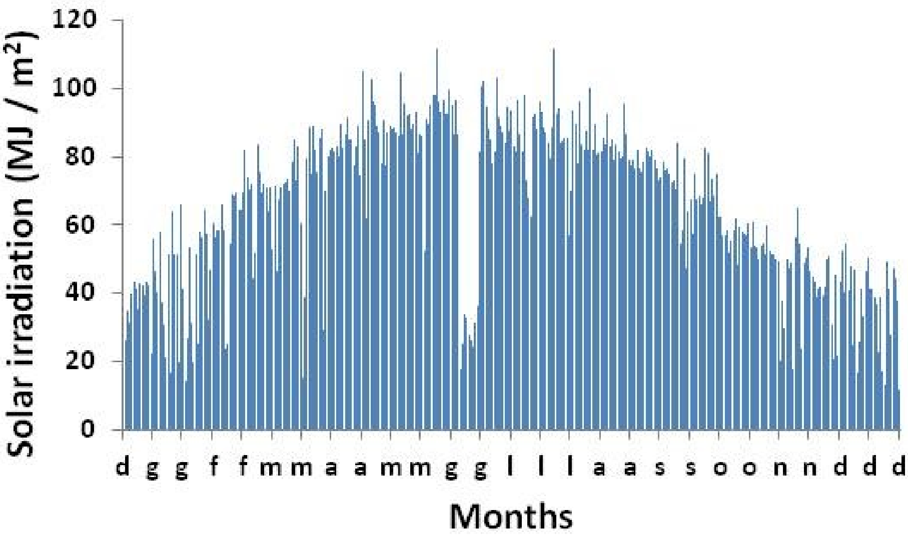


Fig. 12.1 – Instantaneous solar irradiation recorded every 30 minutes during the year (*Elaborations of ARPAS data*).

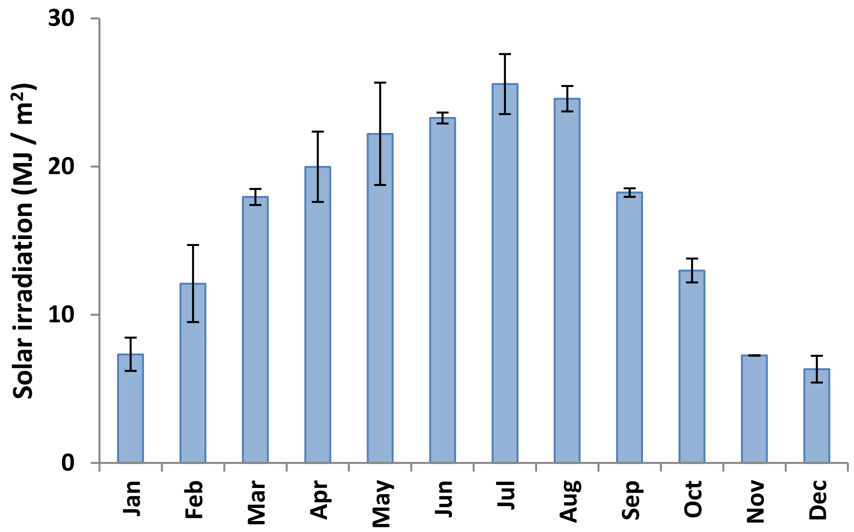


Fig. 12.2 – Solar irradiation (mean ± SE) by month during the three year period 2012-2014 (*Elaborations of ARPAS data*)

The curve in fig. 12.3 describes the distribution during a typical day of the solar irradiation obtained elaborating and averaging instantaneous data recorded during the three year period in the study site. The obtained bell curve shows a peak in the middle of the day.

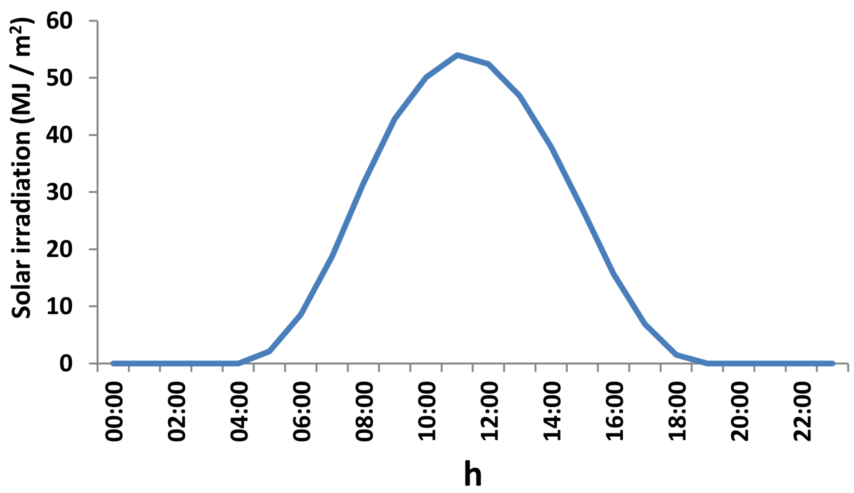


Fig. 12.3 – Hourly distribution of the average solar irradiation during the day in the study site during the three year period 2012-2014 (*Elaborations of ARPAS data*).

12.2 Wind speed

Wind speed trend was studied through elaboration of instantaneous data recorded with a 10 minutes frequency by an anemometer during the three year experimental period.

For these analyses, a total of 148,681 instantaneous wind velocity data have been used. Fig. 12.4 shows the monthly values and their variability during an average year. As a result of analysis of data variability (ANOVA, followed by LSD mean comparison test), no significant differences for wind speed were observed between years and months ($F = 0.63$; $df = 11$; $P = 0.79$).

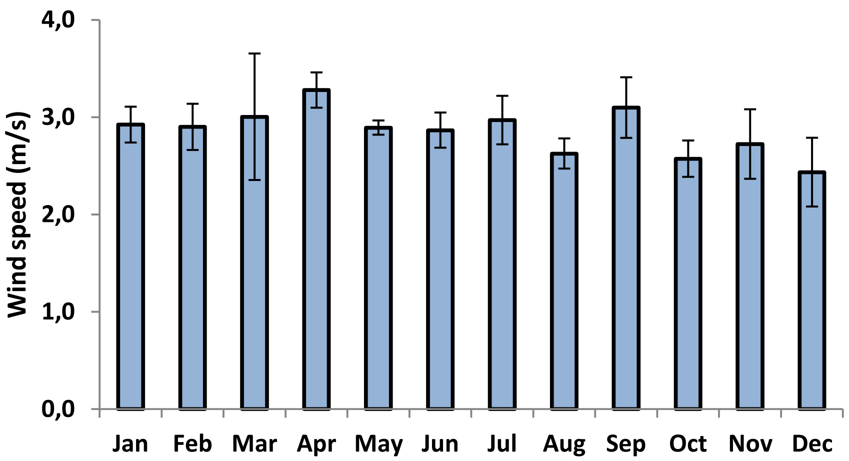
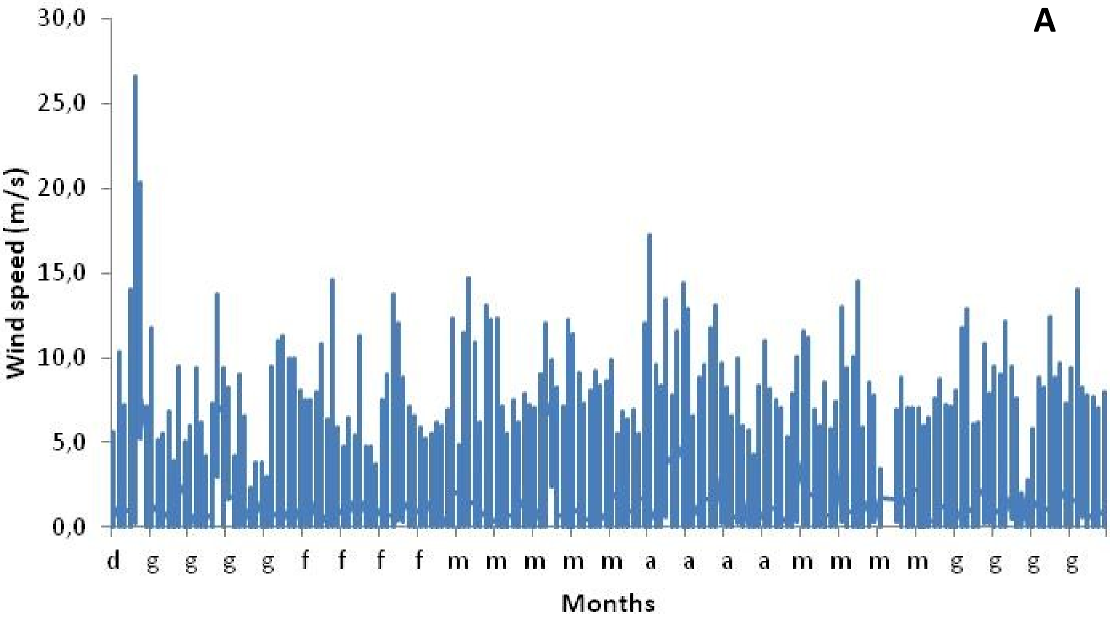


Fig. 12.4 – Monthly wind velocity (mean ± SE) during the average year obtained elaborating three year data (*Elaboration of ARPAS data*).

The annual trend of wind speed instantaneous data is shwon in fig. 12.5 (A and B). Several wind velocity peaks were recorded throughout the year, thus demonstrating a high variability within single months.



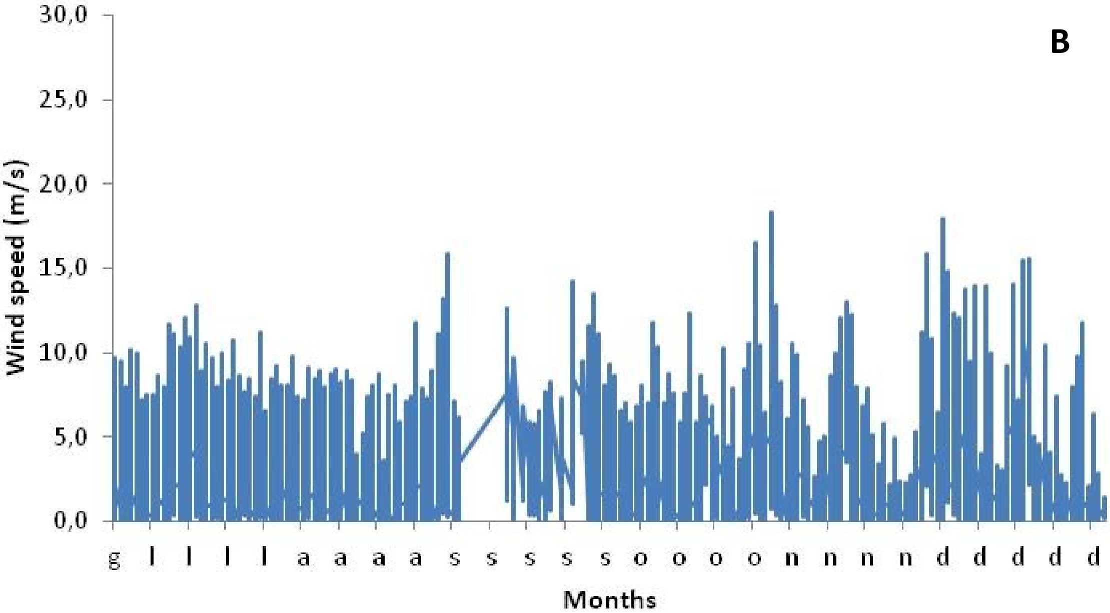


Fig. 12.5 – Instantaneous wind velocity recorded every 10 minutes during the year (A = January/June; B = July-December) (*Elaboration of ARPAS data*).

13 PHOTOVOLTAIC POWER SYSTEM: ENERGY PRODUCTION AND SIMULATIONS

13.1 Photovoltaic energy production monitoring

The actual energy production (kWh) of the photovoltaic system assessed during the three-year-study period (2012/2014), allowed to describe an average annual distribution by month, that ranged between lower values in winter (1,259 kWh in December) and higher levels in summer (3,411 kWh in June). The variability of energy production means among different years was slight and statistically non significant (F = 0.028; df = 2; P 0.9724).

Differences among months during the year were instead significant (F = 40.60; df = 11; P < 0.001), as shown in Fig. 13.1. Annual energy production was on average around 27,544 kWh with just small variations among years (Fig. 13.2).

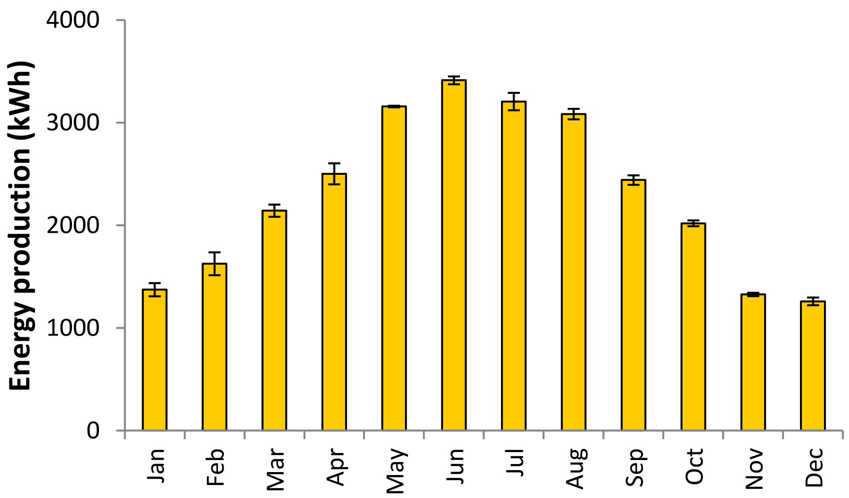


Fig. 13.1 – Monthly energy production (mean ±SE) of the photovoltaic power system during the three-year-study period.

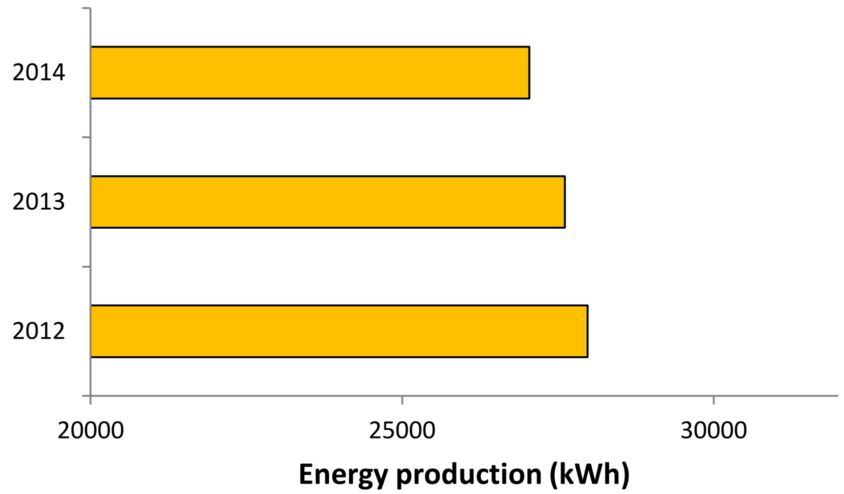


Fig. 13.2 – Comparative representation of annual solar energy production.

13.2 Simulation of the energy produced by the photovoltaic system

Simulations were conducted employing several software applications available on the web and normally used for planning. These data analyses showed a typical seasonal production with monthly values ranging between 1,500 and 3,500 kWh, and a peak in summer (Fig. 13.3).

The environmental data used by software applications for simulations have diverse origin, but they are mostly based on available databases (i.e., ENEA) or on productivity maps (Fig. 13.4). Examining these maps, the value ascribed to the area in which the study farm is located, is 1,400 kWh/1kWp.

As a result of a comparison between average monthly data obtained through simulation and the actual energy production recorded in the farm, a gap of varying proportion is observed, depending on the software employed. Fig. 13.5 shows the relationship between the monthly energy production levels obtained using the software applications OnyxSolar and PVGIS. Either considering actual or simulation values, differences in energy production among months were always significant ($F = 67.06$; $df = 11$; $P < 0.0001$), but no significant differences among output data of the employed software applications were noticed ($F = 0.24$; $df = 11$; $P = 0.7863$). Similarly, despite a general tendency of these applications to over-estimate annual energy production (Fig. 13.6), the statistical comparison between the actual values and the mean of data obtained with different software applications did not highlight significant differences ($F = 3.53$; $df = 1$; $P = 0.1092$).

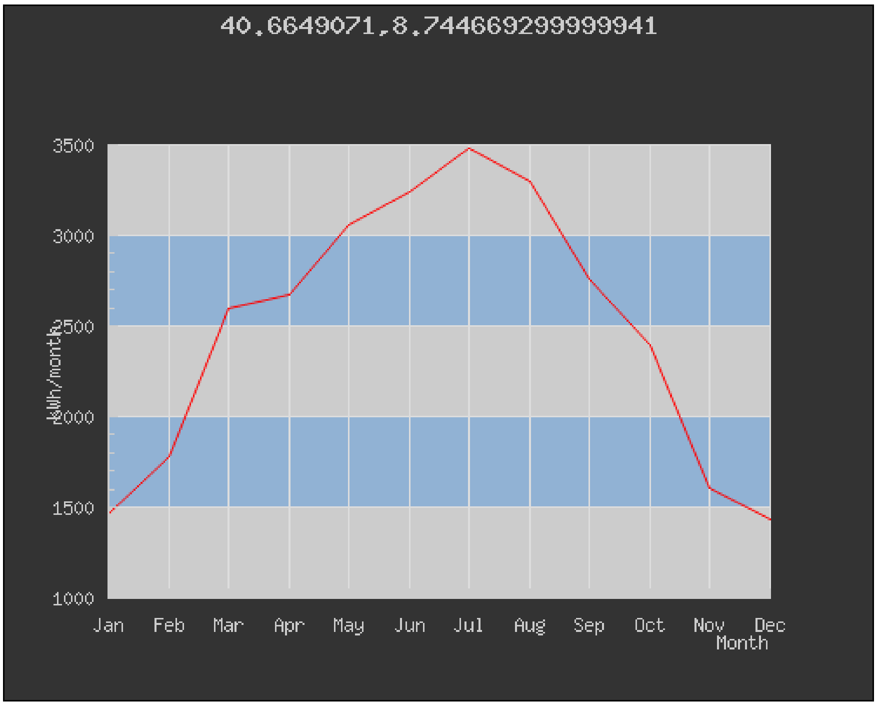


Fig. 13.3 – Monthly energy production of the photovoltaic power system simulated by the smarttools of OnyxSolar.

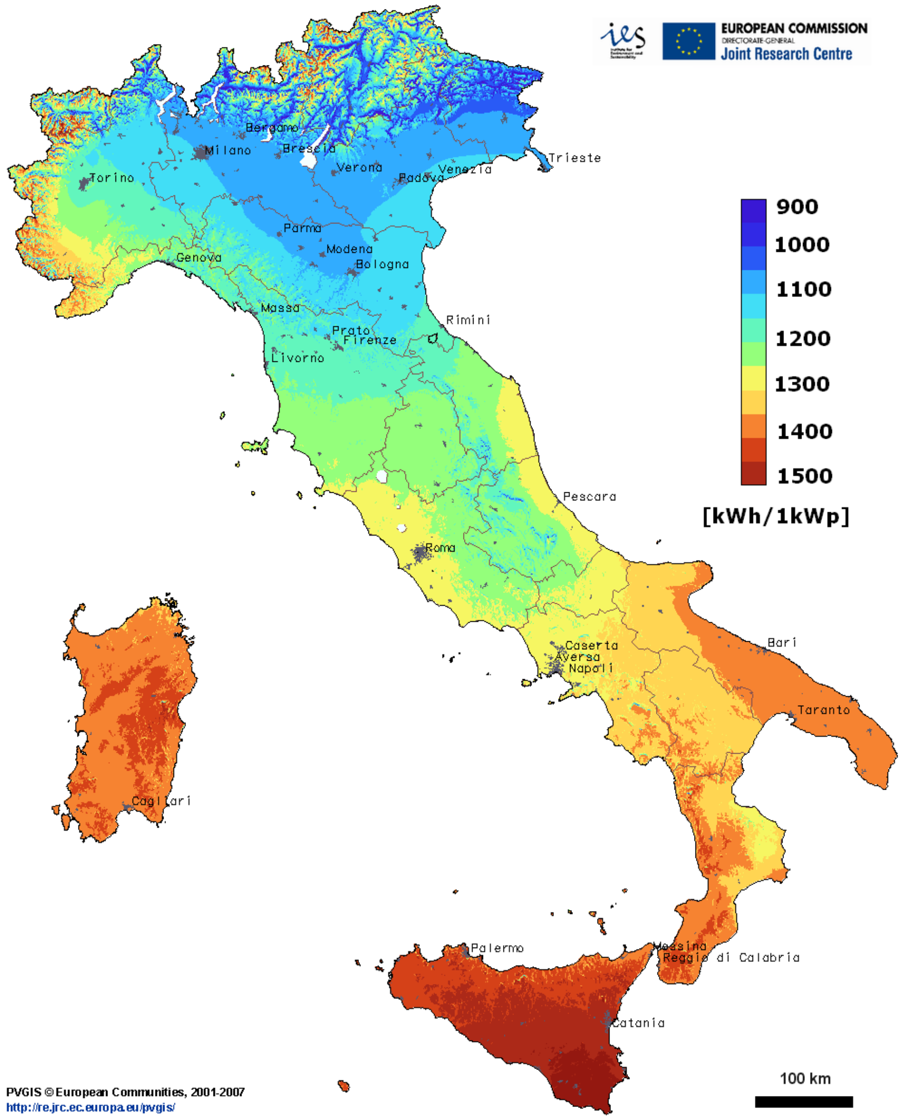


Fig. 13.4 –Energy productivity map used for simulations (*PVGIS*)

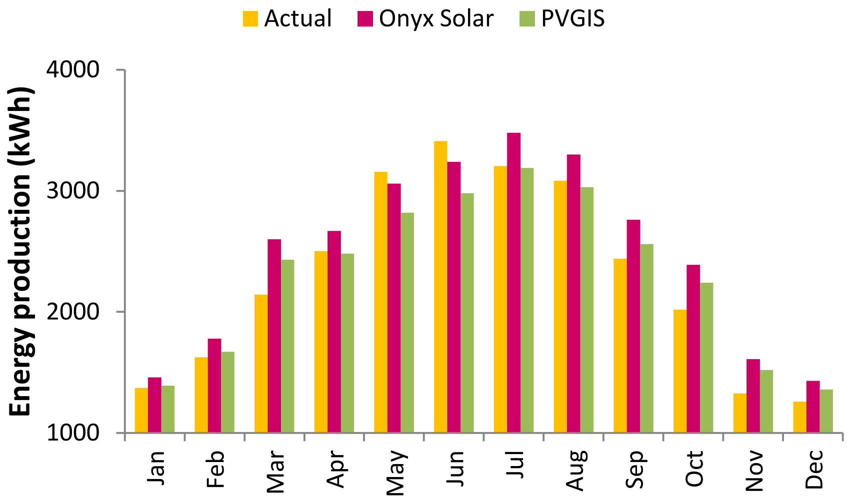


Fig. 13.5 – Representative comparison between actual photovoltaic productions and values obtained by the software applications OnyxSolar e PVGIS

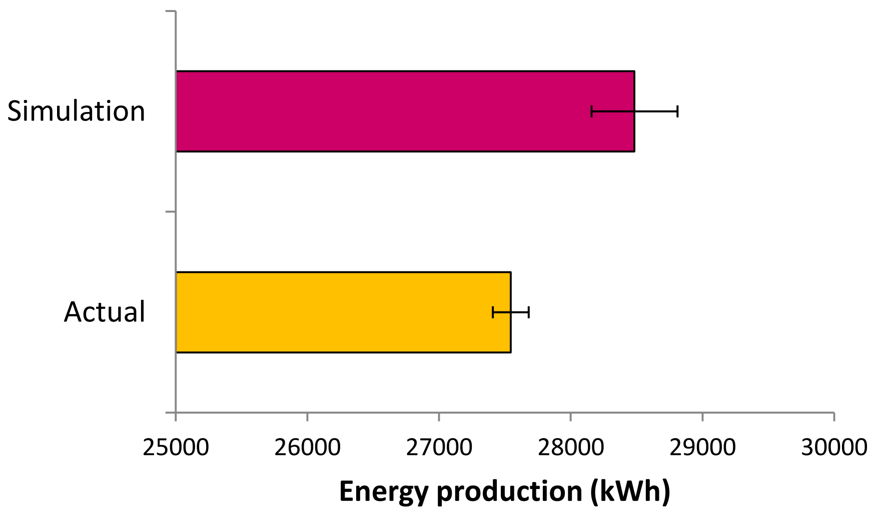


Fig. 13.6 – Average annual energy actually produced by the photovoltaic system compared with simulated values.

14 WIND POWER SYSTEM:
ENERGY PRODUCTION AND SIMULATION

14.1 Energy production by the wind power system

The actual energy production (kWh) of the mini wind turbine, recorded employing the built-in software interface, achieved on average a monthly level of 1,897.27 kWh and a total annual value of 22,770.00 kWh. Annual and monthly data were obtained by processing instantaneous data that show in real time the level of power injected into the network and environmental data (i.e., wind speed) detected by the anemometer installed on the aerogenerator (Fig. 14.1).

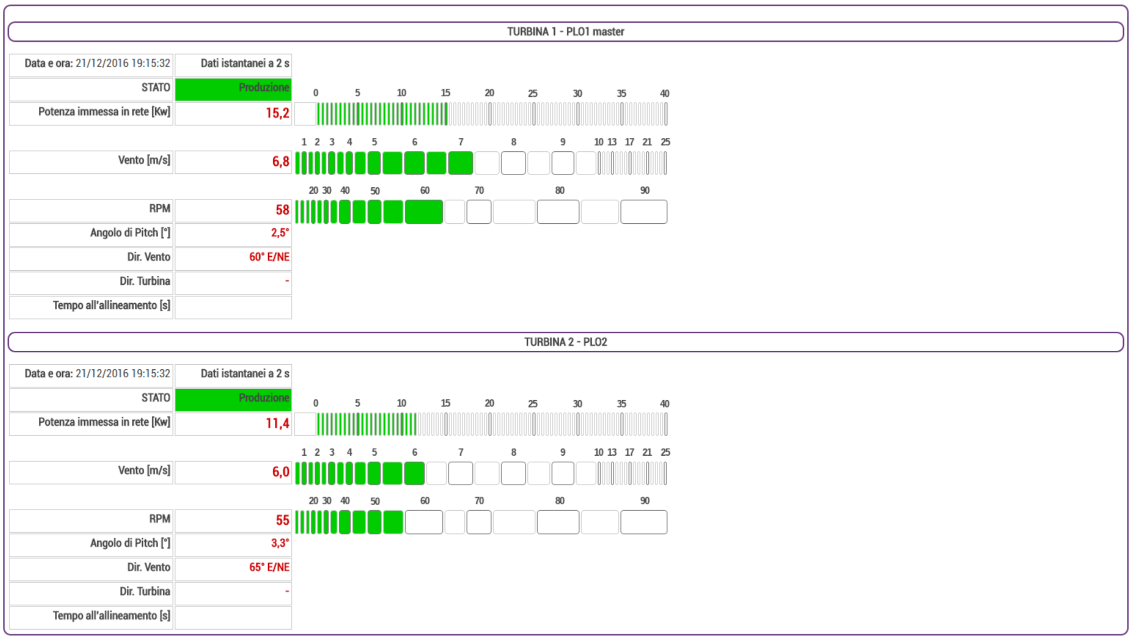


Fig. 14.1 – Representative screenshot of the data recording software interfaced to the wind power system in the farm.

14.2 Wind turbine energy production simulation

Simulations were mostly conducted employing the software SimulWind, that was also used during the planning stages of the plant. Simulations, performed using actual environmental data (i.e., wind speed), led to an estimated annual energy production of 38,178.23 kWh and an average monthly production of 3,181.52 kWh. As a result of analyses conducted with the software, Fig. 14.2 gives a representation of monthly means variability, while Fig. 14.3 shows the average productivity trend during the day, with a pick of around 10.00 kWh during the middle of the day. Comparing monthly productivity means obtained through simulation with actual energy production in the study farm, a significant difference (gap) was observed ($F = 212.82$; $df = 11$; $P < 0.0001$). Fig. 14.4 compares monthly energy production levels obtained with SimulWind with those actually recorded by the wind turbine associated software. In general, a significant overestimation was generated through simulation (Fig. 14.5).

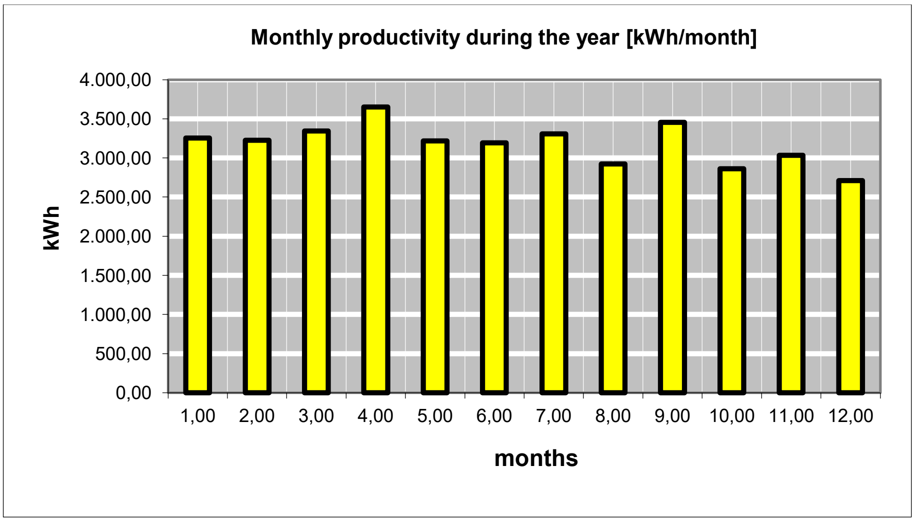


Fig. 14.2 – Average monthly productivity of the wind power system obtained through simulation.

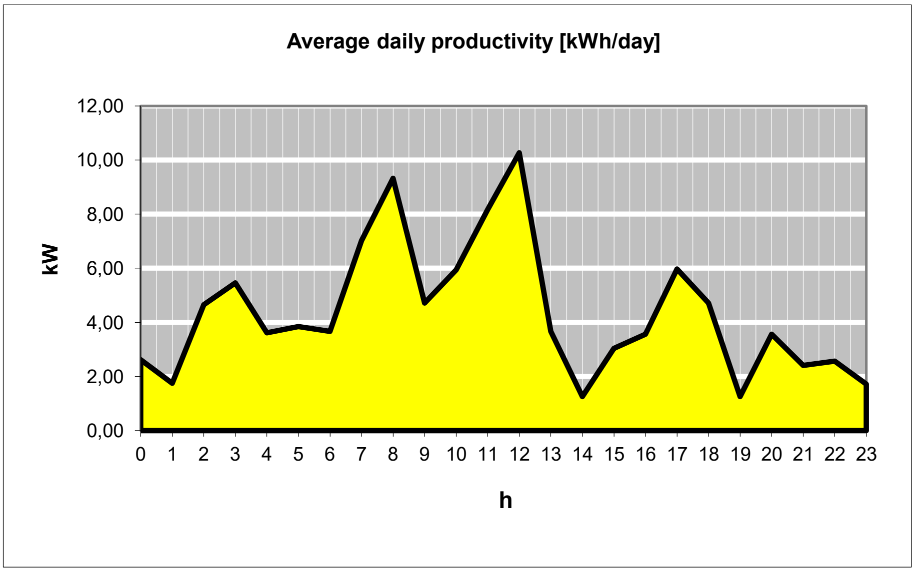


Fig. 14.3 – Average daily productivity of the wind power system obtained through simulation.

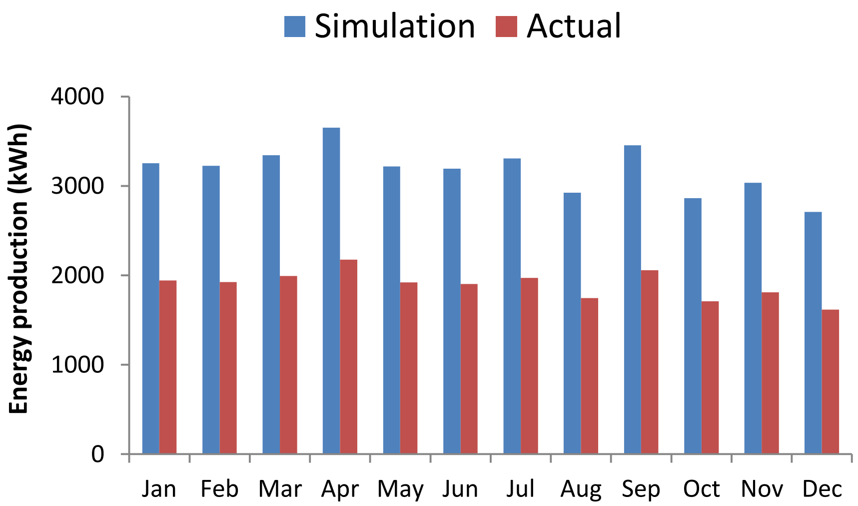


Fig. 14.4 – Monthly comparison between the actual wind energy produced and the result of simulations using SimulWind software.

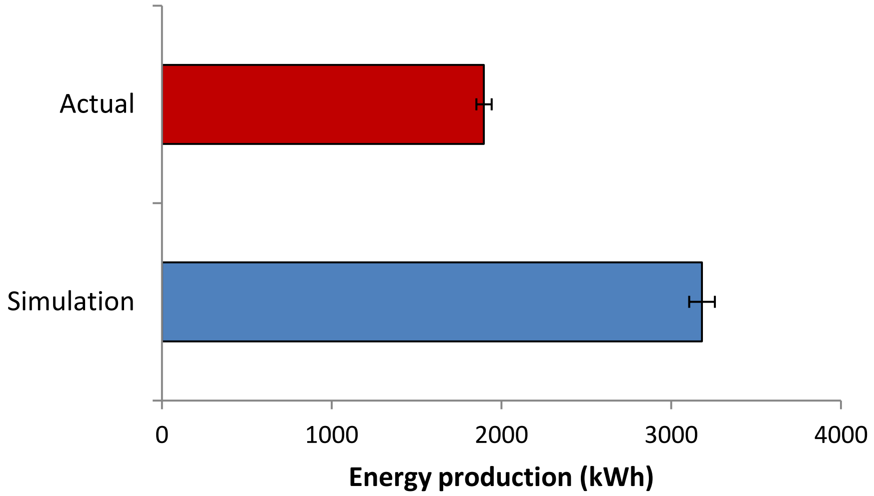


Fig. 14.5 – Comparison between actual and simulated annual wind energy production.

15 ANALYSIS OF ENERGY SELF-SUFFICIENCY IN THE FARM

15.1 Overall energy production by wind and solar power systems

The actual energy produced in the farm from green energy sources in the study period achieved on average 50,311 kWh per year, obtained as the sum of energy produced by the wind and the solar power systems, as shown in Fig. 15.1.

However, such level was significantly lower compared with the average energy consumption in the farm that was around 87,000 kWh, considering the actually employed equipment.

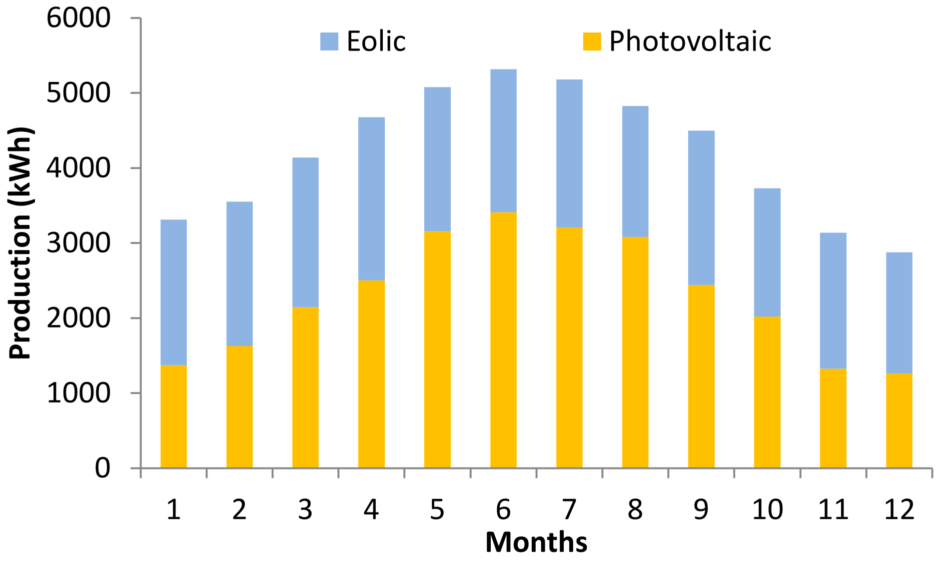


Fig. 15.1 Actual average energy produced in the farm from renewable sources throughout the year.

15.2 Green energy production vs energy consumption in the farm

Because the renewable energy actually produced in the farm is not sufficient to cover the energy consumption needs, further investments to increment the solar power system from the present 20 kW to at least 40 kW are recommended to achieve energy self-sufficiency in the farm.

Fig. 15.2 shows the increment in the total green energy production obtainable throughout the year by increasing the solar power system to 50 kW. According to this new scenario, the total energy produced would allow to cover the energy needed by the newly replaced and less energivorous alternative equipment. In such case, the energy produced during spring and summer, exceeding energy consumption, would compensate the lower production periods in autumn and winter.

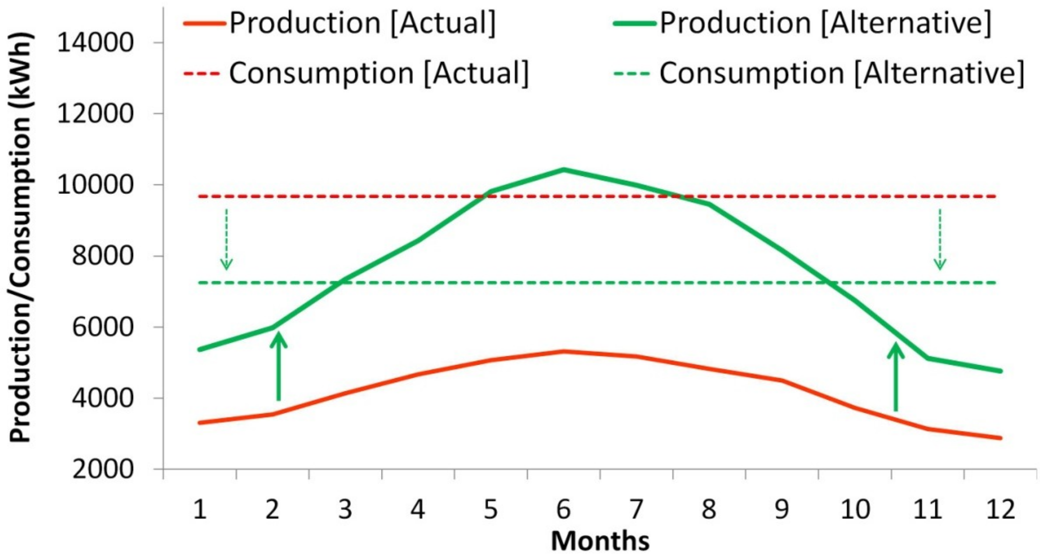


Fig. 15.2 **-** Energy production with actual (present) and alternative (incremented solar power system) green energy systems plotted against actual (present) and alternative (less energivorous equipment) consumption.

DISCUSSION AND CONCLUSIONS

16 DISCUSSION

16.1 Energy consumption in the farm and development of an optimization model

Energy consumtion analyses in the livestock farm allowed to define the overall energy need, taking into account both the energy quality and the distribution of energy demand from the different production cycles. The analytic approach employed in this study led to the determination of the consumption level associated with each piece of equipment, including their relative contribution to the energy balance in the farm. Accordingly, the energy load curves were determined for each device, production cycle, and for the farm as a whole. Besides, the methodology employed allowed to study the farm energy need articulated by energy type and unbundled per usage period (De Corato and Cancellara, 2014).

As expected, major costs for the intensive swine production cycle were represented by operations needed to keep a suitable environment for pigs (Rossi and Gastaldo, 2011). This does not relate only to creating the optimal conditions for production maximization, but also to ensure animal health and wellness. In fact sows are particularly sensitive to high temperatures that affect fertility, newborn piglets need to be maintained at 30-32° C, while the optimal temperature for pig fattening is around 20 °C (Rossi et al., 2011 a and b). These cost items included ventilation, lighting, heating and air conditioning that represented around 98% of the overall energy consumption associated with the swine production cycle. Such scenario is in line with older reports that identified the same items among those playing a preeminent role in the energy balance of pig farming (Baber et al., 1989; De Corato and Cancellara, 2014). However, the recent technology advancements allow a more accurate measurement of consumption levels and the availability of modern equipment, resulting in either significant production increase and potential energy savings (Thornton, 2010).

In the case of the semi-extensive sheep production cycle the higher impact of farm consumption derived from milking and milk refrigeration, that are related to the energy demand from the vacuum pump (milking plant) and the compressor (refrigerator) operation (Pazzona, 1999). Our results are in agreement with several electrical energy analyses conducted in multi-year studies on different animal breeding systems dedicated to milk production (Edens et al., 2003; Upton et al., 2015; Shortall et al., 2016).

The need to reduce energy consumption in animal farming, similar to what is happening in other industries, justifies the continuous search for technological solutions that ensure energy savings, which normally translates into economical and environmental benefits (Hu and Kao, 2007). Such purposes are in line with the more general need to counteract the environment pollution and to meet animal well-being in modern animal farming (Grunert et al., 2004; McLeod, 2011; Petit and Hayo, 2003). In fact, during the last decades, several efforts have been devoted to finding more environmentally responsible solutions for pig production, even if the main focus has been animal feeding (Eriksson et al., 2005) that represents a key component of energy need in swine farming. However, given the high impact of energy costs on the farm balance, besides studying improvements for animal feed ration, it is necessary to implement specific tools for electrical energy management, especially in the intensive swine breeding models common in the Mediterranean environment (De Corato and Cancellara, 2014).

As a result of our investigations on a representative study farm system, the need to satisfy the high energy demand of different equipment and facilities (i.e., lighting, air-conditioning, ventilation, heating) was highlighted. Reducing this energy consumption would be strategic and advantageous not only to benefit the environment but also to enhance overall farm productivity (cost savings). Copious efforts have been carried out to develop methods for energy system optimization (Frangopoulos, 2009) with applications of newly developed mathematical models to different industrial sectors (Méndez-Piñero and Colón-Vázquez, 2013). The application of mathematical modeling for energy consumption analysis and optimization in animal farming is widespread, but mostly focused on feed rations and recipes (Kelemen et al., 2015). However, electrical energy use in the farm should always be taken into account for economical considerations regarding cost minimization and consequent profit maximization.

A good performance of the mathematical models we developed using the software applications Lingo 15.0 and Vensim, was obtained. Following the results of software analyses and simulations, significant savings were demonstrated to be achievable for lighting, ventilation, air-conditioning and heating systems, through the replacement of actual with more energy efficient equipment. More in detail, in the study farm lighting is based on the use of neon light that can be replaced with led light; air-conditioning system including pad cooling can be improved associating an inverter which allows to achieve around 30% energy savings; on-off ventilation system can be similarly improved integrating a variable-frequency drive; heating system relies on traditional heat lamps that can be replaced by variable heat lamps whose heat output and consequent consumption are adjusted by a variable voltage controller depending on environmental parameters (i.e., temperature). The accomplishment of all these savings requires an investment to acquire new equipment, whose amortization cost, calculated for a 5-year period, have been included in annual saving determination. However, the useful life of most equipment is expected to exceed 8-10 years, thus envisioning even higher savings. The results obtained with the application of the mathematical model are consistent with previous studies suggesting specific equipment replacement in swine farming to pursue energy efficiency improvements (Teitel et al., 2008; Zhou and Xin, 2016). In addition our study provides a tool to evaluate the whole farm energy efficiency and takes into account the investment costs. In summary**,** the optimization model developed and applied in this study allowed to identify more energy efficient alternatives and consequently significant savings, as obtained through the solution generated by Lingo software and simulations with Vensim.

Whilst our study was based on a specific case, similar evaluation models can be used for optimization purposes in other swine farms to choose consistent alternatives following a payback method. This would generate meaningful savings that positively benefit the annual farm income statement. Further improvements of our models will provide additional information on its applicability to different kinds of animal farms.

16.2 Environmental potential and green energy production

Sardinia, an island characterized by a typical Mediterranean climate (Palutikof J., 2003), is particularly suited to the exploitation of wind and solar derived energy (Lavagnini et al., 2006; Ghiani et al., 2013).

The environmental parameters we monitored during the three-year experimental period, with special regard to solar irradiation and wind speed, were in line with the expected data averaged from a multi-year analysis conducted in Sardinia by SAR (Chessa and Delitala, 2017). As expected, a typical bell curve was representative of the solar irradiation distribution during the day, while the annual trend was featured by a significant increase during spring and summer, when an average monthly peak around 28 MJ/m^2 was recorded in July. Remarkably, the average monthly levels of solar irradiation during winter were around 10 MJ/m^2, which represents a still useful value to achieve a good performance of photovoltaic power systems. On the other hand, the average wind velocity surveyed at the closer SAR station (Ozieri) was lower than the values recorded by the anemometer associated with the turbine that gave a more truthfully representation of the wind speed in the study site. Such deviance is in relation to the orography of Sardinia that significantly influences the wind (Chessa and Delitala, 2017), and our results suggest that for a proper evaluation of the wind potential as an energy source in a specific area, it is always necessary to take in site measurements and do not rely on data coming from nearby stations. Another aspect that emerged from environmental data analysis, is the deviance between average and instantaneous wind speed. In fact, mean values are not representative of the actual wind turbine operation, which can have a good performance as a result of a temporary but high wind speed (Hau, 2013). For this reason, wind velocity data were collected with a 10 minute frequency, so as to give a more realistic representation of the overtime wind speed variations.

On the other side, an homogeneous distribution of this energy source throughout the year was observed, which supports its continuous exploitation potential in Sardinia (Chessa and Delitala, 2017).

Satisfactory energy production levels were achieved with the rooftop photovoltaic power system with a mean variation range between 1,259 kWh (winter) and 3,411 kWh (summer), and an average annual total production of 27,544 kWh. Remarkably, non significant variations were observed in a comparison among different years within the study period, which proves the stability of solar radiation as a green energy source in a broader sense, either in Sardinia and in areas with similar climatic characteristics (Fioretti et al., 2010). Accordingly, the over the year distribution of the energy produced by the power solar system paralleled the annual solar irradiation trend, being both featured by peaks in summer and lower levels in winter. As a result of the close correlation between solar irradiation and energy production, and of the reliability of either data collected at the survey station and the estimated values reported on the energy productivity maps we selected, a good performance of various simulation software applications was observed in comparison with the actual productivity levels of the photovoltaic power system located on the rooftop in the experimental farm. However, the reliability of a simulation tool is strictly dependent on the quality of the environmental data used, as the output can significantly change depending on the source reliability (Luque and Hegedus, 2003). Besides the uncertainty related to input data, there are several success stories of application and validation of mathematical and simulation models to predict the photovoltaic power system performance in Mediterranean climates (Fuentes et al., 2007). As a result of our study and previous literature in the field, an accurate selection of literature data and, possibly, the availability of truthful information from a nearby survey station, are recommended to ensure new photovoltaic power systems planning accuracy.

More complex was the estimation of the energy production in the case of the wind power system, due to the lack of correspondence between wind speed data collected through a nearby survey station and data recorded by an anemometer integrated with the turbine system. While using wind speed data from the anemometer installed on the aerogenerator represented the sole consistent input option for simulation software, a general overestimation compared to actual energy production was obtained. Considering that several software applications, based on validated algorithms, have proven to generate good quality simulations (Calaf et al., 2010), the accessibility to reliable wind data is essential.

The availability of environment-related information in agro and animal farming, not only is important to make proper evaluations on the photovoltaic and wind turbine power station potential, but also to exploit this natural renewable resources from a wider eco-sustainable perspective (Tilman et al., 2002a), including for instance the energy savings achievable through the exploitation of green roofs (Fioretti et al., 2010) or for the broader application to the agriculture and crop system (Hunt et al., 1998; Fu and Rich, 2002). Similarly, solar radiation features significantly affect animal behaviour and wellness (Finocchiaro et al., 2005; Sevi et al., 2001; Tucker et al., 2008), and wind represents a factor that significantly influences indoor air quality parameters in livestock buildings, and consequently animal wellness and productivity (Morsing et al., 2008).

Everything considered, gathering as many information on the farm environment as possible should be a general objective in modern animal husbandry, especially on the prospect of rethinking animal housing through precision livestock systems (Moshou et al., 2001; Naas, 2002; Nagl et al., 2003; Ning et al., 2006; Shao and Xin, 2008; Fournel et al., 2017). Employing this approach will provide to the famers and his professional consultants both a wider picture on the exploitation potential of a specific climate (i.e., renewable energy production) and a platform to underpin appropriate environment control strategies to improve animal welfare.

16.3 Conclusions

The approach used in this research and the pursuit of the predetermined objectives, have helped to develop a study on the fundamental components of operating energy in animal farming: energy production and energy consumption, both considered in an eco-sustainable way (Tilman et al., 2002b).

The consumption optimization model, obtained through simulation employing different software applications, allowed to identify alternative and more energy efficient equipment that may replace actual instruments and devices to achieve significant energy savings.

The suggested improvements in lighting, ventilation, air-conditioning and heating systems, appear to be a good example of consumption optimization in swine farming.

Because in our case amortization of investment costs have prudentially been calculated on a five-year basis, while a longer equipment life-span (8-10 years) is estimated, further savings are expected. On the other side, the model that we developed and successfully applied to the swine production cycle, can be similarly applied to other livestock systems.

Environmental parameters (solar irradiation and wind speed) considered in this study, together with the use of specific simulation software applications, allowed to accurately estimate the expected energy production levels in the study farm.

Besides simulations based on actual and estimated environmental data, it was possible to consider and compare the output of these elaborations with the actual energy produced by photovoltaic and wind power systems, which allowed to quantify the deviation between actual and estimated values. The output of this study, applied on a larger scale, may allow to define with higher accuracy the expected renewable energy production by photovoltaic and wind power systems in the Mediterranean area.

A regular use of a similar approach for decision making in the farm context, pursuing the objectives of reducing energy consumption and favouring energy production from renewable sources, will translate into both a general economical benefit for the farm and a higher environmental responsibility.

ACKNOWLEDGEMENTS

First of all I would like to express my sincere thankfulness to my supervisor Professor Antonio Pazzona, who made my PhD experience possible. I'm really grateful for his trust in me on this academic commitment and for being always open and fair during my career path.

I extend my gratitude to Doctor Mario Sergio Delitala from ARPAS (Regional Agency for the Environment Protection of Sardinia) for supplying environmental data.

I'm really grateful to Mister Gavino Brandino for his willingness to give access to internal farm data and information during this study.

I would sincerely like to thank Engineer Giovanni Chessa, colleague during this PhD experience and friend, for his technical advice and support for the development of the mathematical model and for the productive brainstorming meetings.

Thanks to my parents for their essential and constant support.

Last but not least, my most precious thanks to Luca… always and forever!

REFERENCES

Bakos G.C., Tsagas N.F., 2003. Technoeconomic assessment of a hybrid solar/wind installation for electrical energy saving. *Energy and Buildings* 35, 139–145.

Barber E.M., Classen H.L., Thacker P.A., 1989. Energy use in the production and housing of poultry and swine – an overview. *Canadian Journal of Animal Science* 69, 7-21.

Bardi U., El Asmar T., Lavacchi A. 2013. Turning electricity into food: the role of renewable energy in the future of agriculture. *Journal of Cleaner Production* 53, 224–231.

Bazen E.F., Brown M.A., 2009. Feasibility of solar technology (photovoltaic) adoption: A case study on Tennessee's poultry industry. *Renewable Energy* 34, 748–754.

Belletti G., Marescotti A., 2015. Economia dell'Impresa Agro-alimentare - Le specificita' dell'agricoltura e l'azienda agricola. Università degli Studi di Firenze, 54 pp. http://www.webalice.it/andrea.marescotti/Didattica/EIAA/EIAA_Disp-01_Processi.pdf

Biondi P., Panaro V., Pellizzi G., 1989. Le richieste di energia del sistema agricolo italiano. CNR, Consiglio Nazionale delle Ricerche, Progetto Finalizzato Energetica, Sottoprogetto Biomasse ed Agricoltura, Report LB-20, Roma, Italia, 389 pp.

Booth L., Stermanb J.D., 2000. Bathtub dynamics: initial results of a systems thinking inventory. *System Dynamics Review* 16, 4.

Borges Neto M.R., Carvalho P.C.M., Carioca J.O.B., Canafístula F.J.F., 2010. Biogas/photovoltaic hybrid power system for decentralized energy supply of rural areas. *Energy Policy* 38, 4497–4506.

Brown-Brandl, T.M.; Nienaber, J.A.; Turner, L.W., 1998. Acute heat stress effects on heat production and respiration rate in swine. *Transactions of the ASABE* 41, 789-793.

Caffarelli A., de Simone G., Stizza M., D'Amato A., Vergelli V., 2009. Sistemi eolici: progettazione e valutazione economica, impianti micro, mini, multi megawatt. Casa Editrice Maggioli Editore, Santarcangelo di Romagna (RN), Italia.

Calaf M., Meneveau C., Meyers J., 2010. Large eddy simulation study of fully developed wind-turbine array boundary layers. *Physics of Fluids* 22, 015110.

Castelli G., Mazzetto F., 1986. A mathematical model for dimensioning Integrated Energy Systems. Proceedings 2nd International Conference "Energy and Agriculture", 13-16 October 1986, Sirmione, Vol. No.3, 392-410.

Castelli G., Mazzetto F., 1988. Manual on design and assessment of integrated energy systems (SIENA simulation model). FAO/REUR Technical Series, No.6, Rome, 1-158.

Chel, A., Kaushik, G. 2011. Renewable energy for sustainable agriculture. *Agronomy for Sustainable Development* 31, 91–118.

Chessa P.A., Delitala A., 2017. Il clima della Sardegna. Sardegna ARPA. Dipartimento Specialistico Regionale Idrometeoclimatico. Accessed on 15 February 2017. http://www.sar.sardegna.it/pubblicazioni/notetecniche/nota2/index.asp

Clarke D.W., 1988. Application of generalized predictive control to industrial processes. *IEEE Control Syst. Mag.* 8, 49–55

Colmenar-Santos A., Campíñez-Romero S., Pérez-Molina C., Castro-Gil M., 2012. Profitability analysis of grid-connected photovoltaic facilities for household electricity self-sufficiency. *Energy Policy* 51, 749–764.

Colón-Vázquez., Melitza., 2011. Sensitivity analysis in the minimization energy cost by combining the PREPA supply with photovoltaic system. Mayaguez : MS Thesis - University of Puerto Rico.

Connelly M.J., 2009. Fatal misconception: The struggle to control world population. Harvard University Press.

Dalwadi P.G., Mehta C.R., 2012. Feasibility Study of Solar-Wind Hybrid Power System. International Journal of Emerging Technology and Advanced Engineering Website: www.ijetae.com (ISSN 2250-2459, Volume 2, Issue 3, March 2012).

De Corato U., Cancellara F.A. , 2014. Analisi dei consumi energetici e miglioramento delle *performance* di efficienza energetica in alcune tipologie di allevamento. In: L'Efficienza Energetica nel comparto zootecnico. RT/2014/16/ENEA (ISSN/0393-3016).

De Gaetano L., 2013. Caratteristiche tipologiche delle aziende agricole. 6° Censimento Generale dell'Agricoltura. Istituto Nazionale di Statistica (ISTAT), 346 pp. http://www.istat.it/it/files/2014/11/TipologiaAziendeAgricole.pdf

De Schutter O., Vanloqueren G., 2011. The new green revolution: how twenty-first-century science can feed the world. *Solutions* 2, 33-44.

Dihrab S.S., Sopian K., 2010. Electricity generation of hybrid PV/wind systems in Iraq. *Renewable Energy* 35, 1303–1307.

Duncan, I.J.H., Petherick, J.C., 1991. The implications of cognitive processes for animal welfare. *Journal of Animal Science* 69, 5022–5071.

Edens W.C., Pordesimo L.O., Wilhelm L.R., Burns R.T., 2003. Energy use analysis of major milking center components at a dairy experiment station. *Applied Engineering in Agriculture* 19, 711-716.

Elhadidy M.A., Shaahid S.M., 2004. Promoting applications of hybrid (wind+ photovoltaic+ diesel+ battery) power systems in hot regions. *Renewable Energy* 29, 517.

Eriksson I.S, Elmquist H., Stern S., Nybrant T. 2005. Environmental Systems Analysis of Pig Production. The Impact of Feed Choice. *International Journal of Life Cycle Assessment* 10, 143-154.

European Commission (EC) Directorate-General for Health & Consumers (2011). – Communication from the Commission to the European Parliament and the Council. Action plan against the rising threats from antimicrobial resistance. EC, Brussels.

FAO La Zootecnia nel Mondo 2011 - World Livestock 2011 Available from: http://www.fao.org/

Finocchiaro R., Van Kaam J..B.C.H.M., Portolano B., Misztal I., 2005. Effect of heat stress on production of Mediterranean dairy sheep. *Journal of Dairy Science* 88, 1855-64.

Fioretti R., Palla A., Lanza L.G., Principi P., 2010. Green roof energy and water related performance in the Mediterranean climate. *Building and Environment* 45, 1890–1904.

Food and Agriculture Organization of the United Nations (FAO) (2009). – How to feed the world in 2050. FAO, Rome.

Fournel S., Rousseau A.N., Laberge B., 2017. Rethinking environment control strategy of confined animal housing systems through precision livestock farming. Biosystems Engineering 155, 96–123.

Frangopoulos C.A. 2009. Methods of energy systems optimization. In: Energy, Energy System Analysis and Optimization, Vol. II, Frangopoulos C.A. (Ed.), EOLSS Publisher/UNESCO, Oxford, UK.

Fu P., Rich P.M., 2002. A geometric solar radiation model with applications in agriculture and forestry. *Computers and Electronics in Agriculture* 37, 25–35.

Fuentes M., Nofuentes G., Aguilera J., Talavera D.L., Castro M., 2007. Application and validation of algebraic methods to predict the behaviour of crystalline silicon PV modules in Mediterranean climates. *Solar Energy* 81, 1396–1408.

Gasch R., Twele J., 2012. Wind power plants. Fundamentals, design, construction and operation, Springer.

Ghiani E., Pilo F., Cossu S., 2013. Evaluation of photovoltaic installations performances in Sardinia. *Energy Conversion and Management* 76, 1134-1142.

Grunert K.G., Bredahl L., Brunsø K., 2004. Consumer perception of meat quality and implications for product development in the meat sector—a review. *Meat science* 66, 259-272.

Hammond G.P., Jones C.I. 2008. Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers - Energy* 161, 87-98.

Hau E., 2013. The wind resource. In: Wind turbines. Fundamentals, Technologies, Application, Economics. Springer Berlin Heidelberg, pp 505-547.

Hu J.-L., Kao C.-H., 2007. Efficient energy-saving targets for APEC economies. *Energy Policy* 35, 373-382

Hunt L.A., Kuchar L., Swanton C.J., 1998. Estimation of solar radiation for use in crop modelling. *Agricultural and Forest Meteorology* 91, 293–300.

Kelemen A., Marginean G.E., Vidu L. 2015. Mathematical modelling and optimisation techniques used in dairy farming. *Animal Science* 58, 290-297.

Kershman S.A., Rheinlander J., Neumann T., Goebel O., 2005. Hybrid wind/PV and conventional power for desalination in Libya–GECOL's facility for medium and small scale research at Ras Ejder. *Desalination* 183, 1.

Lammers P.J., Honeyman M.S., Harmon J.D., Helmers M.J. 2010. Energy and carbon inventory of Iowa swine production facilities. *Agricultural Systems* 103, 551–561.

Lavagnini A., Sempreviva A.M., Transerici C., Accadia C., Casaioli M., Mariani S., Speranza A., 2006. Wind Energy 9, 251-266.

Lingo, 2010. User's guide. Lindo Systems Inc. Chicago, IL, USA.

Luque A., Hegedus S., 2003. Handbook of PV Science and Engineering, John Wiley & Sons, Chichester, pp. 915–939.

Mahmoudi H., Abdul-Wahab S.A., Goosen M.F.A., Sablani S.S., Perret J., Ouagued A., et al., 2008. Weather data and analysis of hybrid photovoltaic-wind power generation systems adapted to a seawater greenhouse desalination unit designed for arid coastal countries. *Desalination* 222, 119.

Manwell J.F., McGowan J.G., Roberts A.L., 2012. Wind Energy Explained: Theory, Design and Application, John Wiley & Sons, 2nd edition.

McLeod A., 2011. World livestock 2011-livestock in food security, Food and Agriculture Organization of the United Nations (FAO).

Méndez-Piñero M., Colón-Vázquez M. 2013. Mathematical Model to Optimize the Energy Consumed by a Semiconductors Manufacturing Industry – An Application. *Journal of Mathematical Modelling and Application* 1, 78-83.

Morsing S., Ström J.S., Zhang G., Kai P., 2008. Scale model experiments to determine the effects of internal airflow and floor design on gaseous emissions from animal houses. *Biosystems Engineering* 99, 99–104.

Moshou D., Chedad A., Van Hirtum A., De Baerdemaeker J., Berckmans D., Ramon H., 2001. Neural recognition system for swine cough. *Mathematics and Computers in Simulation* 56, 475-487.

Murgia L., Caria M., Pazzona A., 2008. Energy use and management in dairy farms. International Conference: September 15-17, 2008 Ragusa – Italy. Innovation Technology to Empower Safety, Health and Welfare in Agriculture and Agro-food Systems.

Naas I. "Applications of Mechatronics to Animal Production". Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Invited Overview Paper. Vol. IV. October, 2002. Presented at the Club of Bologna meeting, July 27, 2002. Chicago, IL., USA.

Nagl L., Schmitz R., Warren S., Hildreth T.S., Erickson H., Andresen D., 2003. Wearable sensor system for wireless state-of-health determination in cattle. Journal of Engineering in Medicine and Biology Society. Proceedings of the 25th Annual International Conference of the IEEE, vol. 4, 3012- 3015.

Ning W., Zhang N., Wang M., 2006. Wireless sensors in agriculture and food industry—Recent development and future perspective. *Journal of Computers and Electronics in Agriculture* 50, 1-14.

Pallabazzer R., 2011. Sistemi di conversione eolica, la tecnologia delle moderne macchine del vento. Casa Editrice Hoepli, Milano, Italia

Palutikof J., 2003. Analysis of Mediterranean Climate Data: Measured and Modelled. In: Mediterranean Climate. H.-J. Boole (Ed.). Springer-Verlag Berlin Heidelberg, pp 125-132.

Pazzona A., 1999. Impianti di mungitura e di refrigerazione del latte nell'allevamento ovino e caprino. Dimensionamento, costruzione e prestazioni. ERSAT. Editrice Estro.

Petit J., Hayo M.G. van der Werf, 2003. Perception of the environmental impacts of current and alternative modes of pig production by stakeholder groups. *Journal of Environmental Management* 68: 377–386.

Thornton P.K., 2010. Livestock production: recent trends, future prospects. Phil. Trans. R. Soc. B 365, 2853–2867.

Pulina G., Francesconi A.H.D, Mele M., Ronchi B., Stefanon B., Sturaro E., Trevisi E., 2011. Sfamare un mondo di nove miliardi di persone: le sfide per una zootecnia. *Italian Journal of Agronomy* 6(s2):e7

Qin Z., Li W., Xiong X., 2013. Incorporating multiple correlations among wind speeds, photovoltaic powers and bus loads in composite system reliability evaluation. *Applied Energy* 110, 285–294.

Reilly M., Willenbockel D., 2010. Managing uncertainty: a review of food system scenario analysis and modelling. Philos. T. R. Soc. B 365, 3049-3063.

Riva G., 1990. Approvvigionamento energetico e tecnologie di conversione, Edagricole, Bologna.

Riva G., Fiala M., Mazzetto F., 1987. Individuazione dei fattori limitanti la diffusione di impianti energetici innovativi attraverso la loro analisi economica. Rivista di Ingegneria Agraria 4, 220-233.

Rossi P., 2011. Consumi energetici e produzione di energia fotovoltaica in zootecnia: La questione energetica esige nuove risposte. *I Supplementi di Agricoltura* 47, 4-5.

Rossi P., Gastaldo A., 2011. Consumi energetici e produzione di energia fotovoltaica in zootecnia: Per i suini i valori cambiano in base al tipo di allevamento. *I Supplementi di Agricoltura* 47, 9-12.

Rossi P., Gastaldo A., Leso L., 2011a. Consumi energetici e produzione di energia fotovoltaica in zootecnia: Le caratteristiche delle stalle incidono sui consumi. *I Supplementi di Agricoltura* 47, 16-19.

Rossi P., Gastaldo A., Pignedoli S., 2011b. Consumi energetici e produzione di energia fotovoltaica in zootecnia: Negli allevamenti suinicoli la ventilazione assorbe il 50% dell'elettricità. *I Supplementi di Agricoltura* 47, 20-23.

Sevi A., Annicchiarico G., Albenzio M., Taibi L., Muscio A., Dell'Aquila S., 2001. Effects of solar radiation and feeding time on behavior, immune response and production of lactating ewes under high ambient temperature. *Journal of Dairy Science* 84, 629-40.

SimulWind, 2013. Guida all'uso. Version 5.0.

Shao, B., Xin, H., 2008. A real-time computer vision assessment and control of thermal comfort for group-housed pigs. *Computers and Electronics in Agriculture* 62, 15-21.

Shortall J., Shalloo L., Foley C., Sleator R.D., O'Brien B., 2016. Investment appraisal of automatic milking and conventional milking technologies in a pasture-based dairy system. *Journal of Dairy Science* 99, 7700-7713.

Spertino, F., Di Leo, P. & Cocina, V. 2013. Economic analysis of investment in the rooftop photovoltaic systems: A long-term research in the two main markets. *Renewable and Sustainable Energy Reviews* 28, 531–540.

Sproul A., 2017. Understanding the p-n Junction. In: Solar Cells. Resource for the Secondary Science Teacher. UNSW Bookshop. http://www.bookshop.unsw.edu.au

Teitel M., Levi A., Zhao Y., Barak M., Bar-lev E., Shmuel D., 2008. Energy saving in agricultural buildings through fan motor control by variable frequency drives.

Tilman, D., 1998. The greening of the green revolution. *Nature*, 396, 211-212.

Tilman D., Fargione J., Wolff B., D'Antonio C., Dobson A., Howarth R. et al., 2001. Forecasting agriculturally driven global environmental change. *Science* 292, 281-284.

Tilman D., Cassman K.G., Matson P.A., Naylor R., Polasky, S., 2002a. Agricultural sustainability and intensive production practices. *Nature* 418, 671-677.

Tilman D., Cassman K.G., Matson P.A., Naylor R., Polasky S., 2002b. Agricultural sustainability and intensive production practices. *Nature* 418, 671-677.

Tina G., Gagliano S., Raiti S., 2006. Hybrid solar/wind power system probabilistic modelling for long- term performance assessment. *Solar Energy* 80, 578-588.

Tucker C.B., Rogers A.R., Schütz K.E., 2008. Effect of solar radiation on dairy cattle behaviour, use of shade and body temperature in a pasture-based system. *Applied Animal Behaviour Science* 109, 141–154.

Upton J., Murphy M., De Boer I.J.M., Groot Koerkamp P.W.G., Berentsen P.B.M., Shalloo L., 2015. Investment appraisal of technology innovations on dairy farm electricity consumption. *Journal of Dairy Science* 98, 898-909.

Vensim, 2016. User's Giude Version 6.

Yang H., Zhou W., Lu L., Fang Z., 2008. Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm. *Solar Energy* 82, 354–367.

Zappavigna P., 2011. Consumi energetici e produzione di energia fotovoltaica in zootecnia: Risparmiare si può, ecco come intervenire. *I Supplementi di Agricoltura* 47, 24-27.

Zhou H., Xin H., 2016. Responses of Piglets to Variable and Constant Wattage Heat Lamps with Clear or Red-Color Radiant Rays. http://www.extension.iastate.edu/pages/ansci/swinereports/asl-1494.pdf. 15/04/2016.

Zhou W., Lou C., Li Z., Lu L., Yang H., 2010. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. *Applied Energy* 87, 380–389.