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**Development of a dynamic simulation model for energy
policies impact evaluation and resource management in
the agro-productive sector**

Relatore: Matteo Vincenzo Rocco

Correlatore: Éric Herbert
Petros Chatzimpiros

Thesis of:

Roberto Pistacchi

ID number 852333

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Nomenclature

Acronyms

AAW	Average Animal Weight
ACE	Average Conversion Efficiency
AMB	Agend based model
BR	Biogas Ratio
BY	Biogas Yield
CAES	Compressed Air Energy Storage
Cattle/cattle	Cattle breeding farm
DM	Dry matter produced
DMF	Dry Matter Fraction
E/P	Energy to Power ratio
Engine/engine	Engine of the developed model
EU	European Union
FBM	Fraction of biomethane in the biogas
FE	Food Energy
FIE	Feed Intake Energy
GE	Gross Energy
Goat/goat	Goat breeding farm
HF	Heat Fraction
LCOE	Levelised Cost of Energy
Lead Acid	Lead Acid battery
LHV	Lower heating value
Li-Ion	Lithium-Ion battery
LP	Linear Programming
ME	Manure Energy
ME	Manure Energy
MF	Manure Fraction
MFA	Material Flow Analysis
MP	Manure production
NE	Net Energy
NPC	Net Present Cost
NPV	Net Present Value
PEMFC	Proton-Exchange Membrane Fuel Cell
Pig/pig	Pig breeding farm
Poultry/poultry	Poultry breeding farm

PV	Photovoltaic
SD	System Dynamics
X	Fraction of AAW
Y	Fraction of MP

Symbols

B	Dimensioning factor
$c_{\text{p,air}}$	Heat transfer coefficient of the air (constant pressure)
$c_{\text{v,air}}$	Heat transfer coefficient of the air (constant volume)
D_{energy}	Energy demand
FHP	Flux of primary products
FHR	Flux of recycled resources
FLP	Flux of waste
FLR	Flux of waste directed to recycling
FRin	Flux of recycling self-consumption
F_s	Storage flux
F_{supply}	Flux of exogenous resources
G	Flux of final products
H	Heat released
IP	Intensity of production
IR	Intensity of Recycling
m_{air}	Mass of air
N	Over-dimensioning factor
η	Engine efficiency
N_{animal}	Number of animals
η_{XH}	Efficiency of the stock of primary resources
T_{ext}	External Temperature
T_{target}	Target temperature
U	Global heat transfer coefficient
V_{air}	Volume of air
XBio	Biogas storage
XH	Stock of primary resources
XL	Stock of waste
X_s	Storage of final products
γ	Recycling conversion efficiency
λ	Coupling factor
Π	Arbitrary transfer function

Extended Abstract

1. Introduction

1.1 The EU targets and the agro-productive system

The emerging policies aiming at reducing GHG emissions are always more promoting the introduction of renewable energy technologies, distributed energy resource deployment and technological innovation. The EU set the target of at least 20% renewable energy in the energy mix by 2020 and at least 27% by 2030 [1]. The shift to renewables is a big challenge because implies the introduction of intermittent energy sources that are not continuously available for conversion into electricity. Moreover, it is required a profound change in the whole electric system, moving from centralised to decentralised and distributed generation, with continuous development of new solutions.

The residential sector and the several productive sectors characterizing economy will be clearly influenced by this energetic revolution. It is important to understand the impact of different energy policies on these sectors to find suitable solutions. This study in particular focused on the agro-productive sector. The agro-productive sector is an interesting subject because has the advantage to simplify renewable installation thanks to large spaces available. It contains the great energy potential of "Bioenergy" that can be extracted from its waste to produce heat, electricity and fuels. Rural areas are generally characterized by "lower services" in terms of national grid and can be more attracted by self-sufficient renewable solutions.

The relation existing between the agro-productive sector and renewable energy is a complex problem that implies the description of real farms and farmlands and several renewable technologies at the same time.

Due to the high number of variables characterizing the system (e.g. climate conditions, typology of farm, bioenergy production from bio-waste, technologies used, energy storage...etc.), the level of complexity is extremely high. In these terms, the study of several interacting farms supplied using distributed energy solutions requires the use of models able to formalize reality in a compact and manageable way, keeping at the same time a discrete level of details for correct pre sizing of the power plant and reasonable estimations of the production process.

1.2 Brief literature review and model definition

Literature presents several simulators for farms (e.g. CAPRI and X-farm [2],[3]). They are generally based on input-output approaches but the attention focus more on the agricultural aspect. Energy is considered an input necessary for the proper functioning of the system and is simply accounted. The study of correct renewable solutions in the agro-productive sector cannot be reduced to a simple accounting of energy demand. It requires the development of dynamic simulations that show the matching between supply and demand, the use of storage systems and biogas production as by-product of the production process. Frisk [4], for the simulation and optimization of a hybrid renewable energy system for farms located in Cuba, develops a methodology to estimate farms energy demand and biogas production from manure but they are used as inputs for a famous microgrid software called HOMER [5]. This solution is effective but does not permit to have a compact and reproducible approach. Herbst et al. [6], list the principal energy system models used today. There are macroeconomic energy models based on top-down or hybrid approach suitable for regional or multi-regional studies (e.g. World Energy Model (WEM) and Osemosys) These models are suitable for energy forecasting in national contests but they hardly fit to local contests and cannot describe the internal dynamics of the single sector. Other models focus on the impact of different energy policies on the system [e.g. Policy Analysis Modelling System (PAMS) or System Dynamics (SD)]. Mutingi, Mbohwa and Kommula [7] suggest the use of SD for energy policies modelling and evaluation. SD is effective to study the impact of different policies because considers causality relationships between system variables, causal loops, feedback structures and time delays that permit to describe all possible implications. The limit is in the resource management and the lack of a structure for a compact material flow analysis between interacting agents. Finally Cong, Cahill and Menzel [8] made an analysis of energy simulation tools in the building environment. Even if highly detailed, these models represent “passive” energy loads and cannot describe the dynamics of the production process inside the building.

1.3 Objectives

The general objective of this study is energy policies impact evaluation and resource management for productive systems in the agro-productive sector. All around Europe there are geographical site dedicated to intensive production of animal and

vegetable products. In Bretagne (France) for example, is possible to find 16 or more exploitations in 10 km² [9]. For all reasons explained in chapter 1.1 and thanks to the high density of exploitations achievable, these systems are particularly interest. It is important to have tools that permit to analyse the impact of renewables and distributed generation on their production process to support the achievement of European targets and reduce GHG emissions of the agro-productive sector, which is among the principal responsible [10].

Since models suitable for the purpose of this study are not available in literature (excluding not free of charge and elaborated software as HOMER), a suitable model have been conceptualized and developed using Python 2.7, an open source programming language.

More specifically, the model have been used to study the possibility for poultry, pig cattle and goat farms located in Île-de-France (France), to be energetically self-sufficient using renewable energy, energy storage, microgrids and bio-methane exchange. The considered energy demand focus on the internal needs of the farms and does not consider indirect or related to transport requirements. The objective is to understand what is the minimum plant size required, costs, and affordability of the related project.

2. Model and methods

This chapter aims to describe the principal characteristics of the model and its principal outputs. How the inputs of the model have been characterised and the methodology used to perform an economic analysis.

2.1 Introduction to model and methods

As definition, the model is a *Dynamic Simulation model* based on a *bottom-up approach* suitable for *local applications* and *techno-economic analysis*.

Figure 1 gives a general description of its working principle. Resource management is the basic task of the model. The simulated system can directly convert resources exogenously produced in final products, exchange them between the sub-systems (S1, S2...Sn) characterizing the global system, store them or recycle them. Recycled resources can be internally consumed to support exogenous production or sent to an external economy. In order to manage a high number of flows and stocks in a compact way, the logic used follows the material flow analysis (MFA) [11].

According to the mass-balance principle, the mass of all inputs into a process equals the mass of all outputs of this process plus a storage term that considers accumulation or depletion of materials in the process. If inputs and outputs do not balance, one or several flows are either missing or they have been determined erroneously.

Since the model is dynamic and represents production processes, the internal dynamics of the system could modify Resource Demand (e.g. the intensity of production reduces or increases). Resource demand is an input for the model but a feedback logic permits to System Evolution and Dynamics to modify it during the simulation. System Performance is the principal output of interest because quantifies for example the capacity of different energy mix to sustain production. The second output is Impact of Resource Scarcity and can be evaluated connecting system efficiency with demand satisfaction (using an exogenous relation set by the user). Due to the unpredictable nature of renewables, could happen that energy production does not behave as desired. It is interesting to know the impact of unfilled demand on the production process.

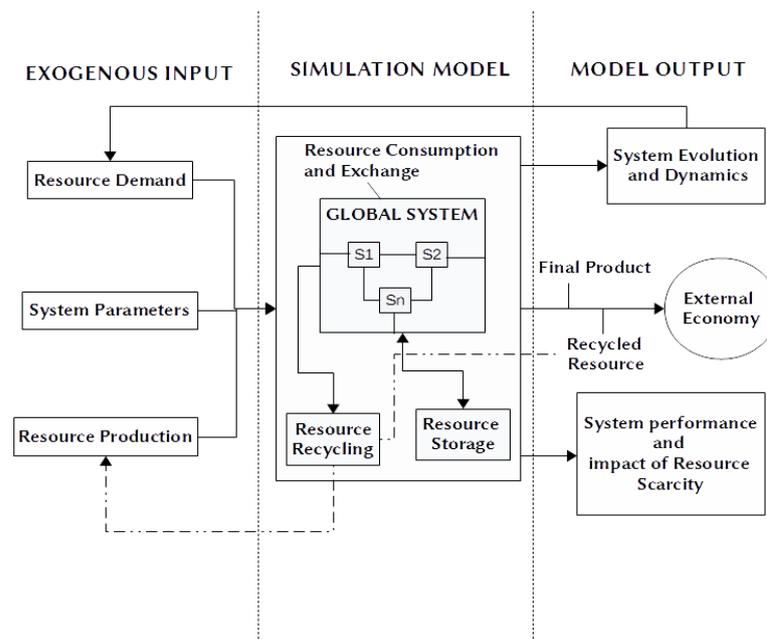


Figure 1 – general description of the model working principle

The system looks at economy as something exogenous so it is not possible to understand the effects of different energy policies on the macroeconomic environment.

2.2 Model structure – The farm

What substitutes the black box characterizing any process in the MFA, in this model, is the engine represented in *Figure 2*. It derives its theoretical bases from the work of Louis-napoléon , Giraud, Herbert et al. [12] that looks at macroeconomic dynamics as thermodynamic engines and from the basic concept of input-output analysis [13]. IP represents the intensity of production while η is the efficiency at which resources are converted in final products. They are not parameters but variables and can vary if influenced by exogenous factors. Resources are extracted from the stock of primary resources XH or come directly from an exogenous supply. XBio is the fraction of XH dedicated to biogas. Electricity and biogas are different form of energy and are treated separately. The waste is directed to the stock of waste XL. IP can be demand driven or less, in the second case, the storage of final products helps the engine absorbing or giving resources. ΠH and ΠL are arbitrary transfer functions that can be used to analyse delays or inefficiencies of the production process.

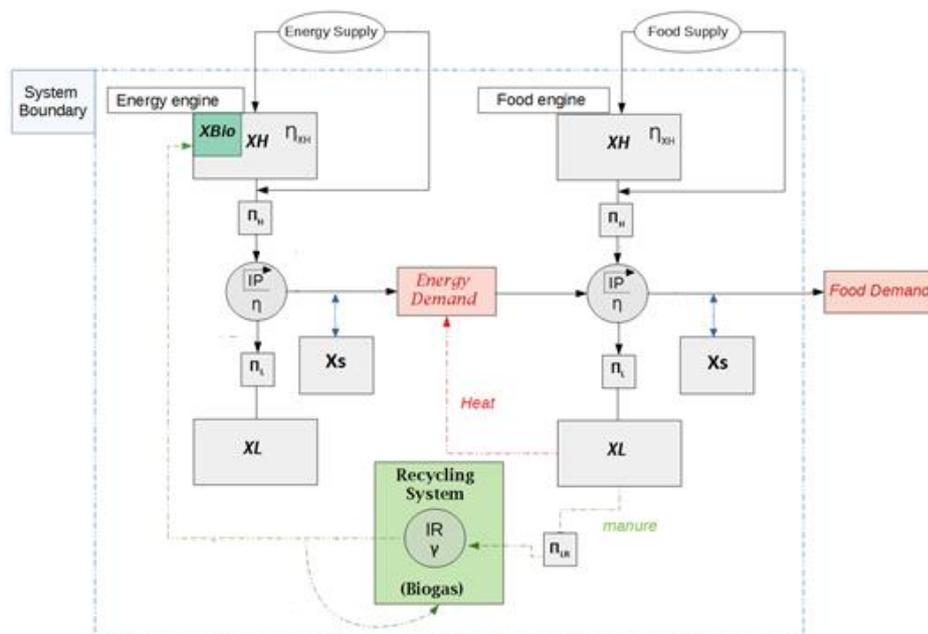


Figure 2- Model structure

Food and Energy engine

The model represents animals production with the engine just described. Animals, in reality, convert the energy contained in their feed in three principal outputs: food (milk, eggs, meat...) that is the useful product, heat released by their body due to

metabolism and thermo-regulation, and manure [14]. Considering the fraction related to food production as the efficiency of the engine, the analogy becomes coherent. Heat and manure are the by-products/waste of the production process. The food engine is the “animal engine” multiplied by the total number of animals in the farm.

The energy engine represents energy uses as ventilators, heaters, pumps... used to satisfy endogenous requirements of the farm. It is a “multiproduct engine”, meaning that it produces more than one product using the same resource. The user sets the priority of one product respect to another.

The two engines work with the same working principle, what differs between them is that while the food engine produces for an external economy, the energy engine produces for the internal needs of the farm. A reciprocal influence is present between the two engines, in fact, satisfaction of energy demand influence directly food engine’s efficiency because it is energy that permits to keep the desired conditions inside the farm. At the same time, the food engine produces heat and manure as waste. The first influence directly energy demand, the second can generate additional units of primary energy (biogas), which can be stored or directly consumed. The reciprocity between the two engines becomes a compact and efficient method to study the adaptability of the agro-productive system to different access to energy.

The recycling system working principle is the opposite of the engine one. IR is the intensity of recycling at which the plant works. In order to produce the flux of recycled resources, depending on the recycling efficiency(γ), the recycling system extracts an amount of waste from XL and consumes an amount of resources, which can be self-produced (as in the biogas case) or exogenously supplied. Notice that here there is only one arbitrary transfer function. For the recycled system, XH and XL are different resources and the presence of a transfer function could be misleading.

Fair and proportional exchange of energy

As in reality, also the model make a distinction between exchange of electricity and exchange of methane. The “stock and flow” logic used to model the single farm permits to interconnect easily several farms considering the exchange as flows of resources moving from one stock to another. Once interconnected, the priority pass from the single farm to the system. Meaning that the single farm could reduce its personal energy demand satisfaction to maximize that of the system.

The logic used for energy exchange is “fair and proportional”. Energy is distributed proportionally to the demand and there is no reason why one farm should receive while another should not if both require energy.

Any farm decide first to satisfy its personal demand, and then the excess energy will be shared between the other farms.

If the energy exchange is “instantaneous” such as microgrids, the system can be considered demand driven and will try to satisfy global demand redirecting flows from one stock to another. If the exchange is not instantaneous such as bio-methane transferred through trucks, then the logic is to pre-determine when the exchange must happen and equalize all the stocks at the average value to keep the fair and proportional logic. This assumption adapt easily to pipelines case. Exchange through tracks can require more time-steps.

2.3 Model inputs

Resource demand

The evolution in time of the inside conditions of a shed can be modelled, without appreciable errors, with four principal contributions: ventilation, heat released by animals (Heat Animals), heat transfer through the walls of the shed (Heat transfer) and energy consumed to keep the energetic balance (Energy).

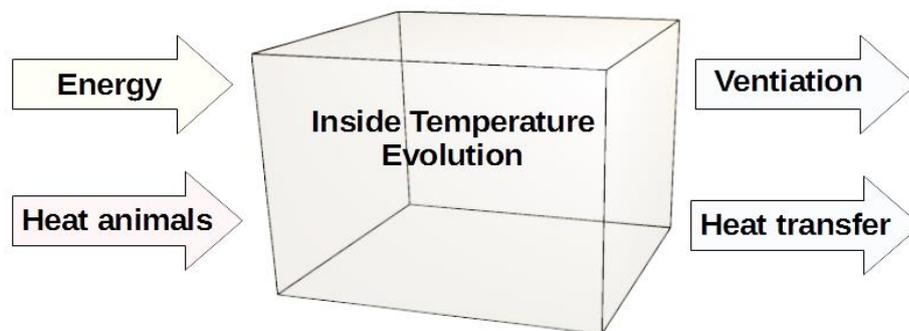


Figure 3 - Energy balance inside the farm

$$\mathbf{Energy = (Ventilation + Heat transfer) - Heat Animals} \quad (2.1)$$

It is possible to evaluate any member of equation (2.1) knowing that the inside temperature must be kept within certain target levels. If the sum of Ventilation and Heat transfer is higher than Heat Animals, the Energy term will be positive

(heating). Vice versa, it will be negative (cooling). If the animals are not closed in a shed but live in an open space, the internal temperature is approximated to the external one.

Other resource demand not evaluable with these equations are extrapolated directly by literature.

Criteria to size the renewable plant

A compact and simple methodology to compare different energy mix have been developed to simplify the comparison between several plant alternatives that aims to be 100% self-sufficient. It is possible to imagine at the national grid as an ideal plant, perfectly dispatchable and sized to produce in the year exactly what is required. The limits of renewable production can be analysed trying to make the same assumption. If the renewable plant is sized to equalize annual production and annual demand, it likely will not satisfy demand any time step because production does not follow always demand (not dispatchable source).

Any power plant is sized to equalize annual energy production and demand. *This condition is expressed saying that N (over-dimensioning factor) is equal to one.* What differentiate an energy mix to another will be the capacity to meet demand any time-step (percentage of demand satisfaction).

2.4 Economic Analysis

The model is not able to perform an economic analysis but gives the principal information necessary to do it. The economic analysis have been performed with excel and is based on the Levelised Cost of Energy (LCOE) and the Net Present Value (NPV) or Net Present Cost (NPC = - NPV).

The LCOE explain what should be the revenue of any single kWh produced by the considered power plant in order to recover all costs within its lifetime. Anyway, in this study energy producer are also consumers, biogas can be converted in different forms of energy and is considered energy exchange. For this reason, the LCOE is supported by the NPV-NPC that, having benefits contained in its formula, better describes the evolution of the investment and permits to compare more accurately different alternatives.

3. Case Study

All climate data and data related to photovoltaic and wind turbines production come from the database of the LIED-PIERI (Laboratoire Interdisciplinaire des Energies de Demain- Paris 7 Interdisciplinary Energy Research Institute) where part of this thesis have been developed.

In particular 7 climate data [from 2006 to 2012] are used for 4 animals (poultry, pig, cattle and goat). 28 farms are simulated to derive average values and analyse energy exchange effects. [For energy exchange as assumption, any climate data is considered as fictitious geographic location].

Principal characteristics of energy and food demand

Poultry: The interest focus on both intensive production of meat and eggs. 2 stages of life: chicks and chickens. Efficiency 22%. Daily dry matter intake demand equal to 8% of its body weight Energy demand is principally characterized by heating and ventilation [15],[16],[17]

Pig: The interest focus on the production of meat. 3 stages of life lactating, nursery and growing pig. Efficiency 18%. Daily dry matter demand equal to 4% of its body weight. Energy demand is principally characterized by heating and ventilation [18]. [16],[19].

Cattle: The interest focus on milk production (efficiency 18%). Only adult animals. Daily dry matter demand equal to 3% of its body weight Daily bio-methane produced 5.77 kWh. Demand is principally related to milk extraction and storage [20], [16] ,[21]

Goat: The interest focus on milk production (efficiency 18%). Only adult animals. Demand is principally related to milk production and extraction. Daily dry matter demand equal to 4% of its body weight Daily bio-methane produced 1.13 kWh. Demand is principally related to milk extraction and storage [22]. [16]

Principal characteristics of energy production and storage

Wind Turbines: Horizontal axis wind turbines production data derive from the work of Marie-Cécile Dupas [23]. The modelling is based on a semi-realistic she derived power production using theoretical efficiencies with reference [24]. No nominal power considered. Cut-in velocity is considered 2 m/s. In order to give a reference size to this ideal technology it is consider that for 3900 working hours, the velocity of the wind is indicatively between 5-9 m/s for 1700 hours, higher than 9 for 150

hours and lower than 5 for 2050 h. The reference velocity is assumed 7 m/s that corresponds to around 130 W/m² of nominal power. Annual production 1075 kWh/kW - 160 kWh/m². *The reference power is not necessary to size the plant because the sizing criteria is based on the kWh produced in the year (see chapter 2.3) but is used to perform the economic analysis.*

Photovoltaic Panels: PV panels production data derive from the work of Gabriel Mostefa [25]. Reference technologies is BP 585F mono-Si and the evolution of the efficiency is estimated using the equations suggested in [26] as reference. Yearly production 1145 kWh/kW-128 kWh/m².

Distribution losses are equal to 6.5% of plant production for the microgrid[27] while considered negligible in the stand alone case.

Biogas production: Since the model aims to internally produce biogas, a methodology have been suitably developed to estimate biogas production starting from the energy contained in the animals' manure. Once known the amount of manure produced by any animal every day[28], the amount of dry matter (DM) available is estimated with [29] while [30] for biogas yield [m³/kgDM]. It is considered that all the manure produced each day is introduced in the digester in order to exploit all bioenergy available. The organic loading rate (OLR) and the plant size is then compared with literature [31] to ensure that the plant is in the range of farm scale applications. The correct order of magnitude is checked also for biogas production using the work of Kafle and Chen [32]. They used different statistical models to predict the biochemical methane potential of different livestock manures. Literature results are, respectively for poultry, pig cattle and goat, 0.3, 0.429, 0.18 and 0.19 m³/kg_{DM}. Model results are respectively 0.395, 0.37, 0.24 and 0.27 m³/kg_{DM}. Biogas digester %self-consumption, 22% [33] .

Batteries : Technologies considered are LI-Ion (round trip efficiency = 95%), and Lead Acid Batteries (round trip efficiency = 82%) [34].

PEMFC storage system: Three principal components that structure hydrogen storage systems are the electrolyser, which use electric power to separate hydrogen from water. The hydrogen tank, where hydrogen is stored at high pressures. The fuel cell stack, which use hydrogen to produce electricity, releasing water. The round trip efficiency (35% as reference [35]) takes into account losses in the electrolyser, tank and fuel cell. Moreover 10% of the energy contained in the hydrogen is considered internally used to compress it at high pressure [36]. The resultant efficiency is 31.5%.

CAES: (round trip efficiency = 65%) [34]. The working principle of CAES starts from the electric motor/generator. Using electricity coming from renewables the motor run the compressor to inject air in the storage tank at relatively high pressure.

When electricity is required, the pressurized air is heated up and expanded in the expansion turbine that drives the generator for power production. The cost to store air depends on the site geology.

Energy to power ratio (E/P): Li-Ion 0.5 h [34], Lead Acid 10 h [34], CAES 160 h [37], [38], Hydrogen 840 h [39]. The energy to power ratio is an important variable to study self-sufficiency targets. Since all the energy required in the year is internally produced, if supply and demand do not match for long periods, the peak storage could become very high compared to the power unit used to supply the single farm.

	<i>Investment cost [€/kW]</i>	<i>Investment cost [€/kWh]</i>	<i>O&M cost [[€/kW/y]</i>	<i>Estimated Lifetime [Years]</i>
<i>Wind turbines</i>	1525	-	50	25
<i>Photovoltaic</i>	1730	-	24	25
<i>Biogas</i>	4000	-	160	25
<i>PEMFC storage* system</i>	3820	10	30	10**
<i>CAES*</i>	1950	10 -40	95	25
<i>Lead Acid battery</i>	-	120	10	10
<i>Li-Ion battery</i>	-	610	10	16

Table 1– Power plant and storage system costs

* Investment cost per kWh for CAES and PEMFC is exclusively the cost of the tank. The total investment cost is the sum of the two investment costs of Table 7

**10 years refers to the lifetime of the PEMFC stack. Lifetime for PEM electrolyser and hydrogen tank are respectively 15 and 25 years

All costs referred to wind turbines, PV panels and bio digesters have been calibrated using [40], [41], [42],[43]. Costs referred to storage systems have been calibrated using [35], [34], [44],[45] for batteries and fuel cells while [46],[47],[34] for CAES systems.

Investment costs refer to total installed costs and take into account all additional tools required (as inverters) for any technology. Lifetime for wind turbines, photovoltaic and anaerobic digesters range between 20 and 30 years depending on the manufacturer, here have been set 25 years for each technology since it is also

the project lifetime. CAES systems have generally life expectancy higher than 25 years. Batteries lifespan have been estimated using [34] and are average values of the different technologies presented. Hydrogen fuel cell stack and electrolyser lifespan is estimated using [35], the tank can range between 20 and 30 years depending on the typology used (25 years as average).

Other assumptions: No technology is supposed to reduce efficiency in the years. The same reference costs are considered for both stand-alone and microgrid applications.

4. Results

Energy demand

	<i>Average Demand</i> [Wh/m ² /h]	<i>Heating</i>	<i>Ventilation</i>	<i>Milk extraction/storage</i>	<i>Other electrical uses</i>
poultry	46	94%	4%	X	2%
pig	45	50%	46%	X	4%
cattle	8.5	X	1.5%	79.5%	19%
goat	5.2	X	1.5%	75%	23.5%

Table 2 – Share of the principal energy uses inside farms

Poultry have demand almost exclusively characterized by heating. Pig largely consume for Ventilation because adult pig need high levels of ventilation in the year. For cattle and goat, production is related principally to milk production and they do not have heating. Adult Cattle and Goat can accept very low temperature respect to pig and chickens. Demand for poultry and pig is largely higher respect to cattle and goat due to heating and the high level of ventilation required for thermo-regulation in the building.

Energy production

Figure 4 gives a graphical resume of the scenarios that have been analyzed in this study. The voice “Renewables” refers to a mix of 65% wind turbines and 35% photovoltaic. This mix is chosen because is the one that maximize demand satisfaction in the year. What can be deduced is that, farms contain the potential

to be energetically self-sufficient without oversizing energy production. The higher is the complexity of the system the higher will be self-sufficiency.

The simple use of renewables (photovoltaic + wind turbines) permits to achieve just between 30-40% of demand satisfaction. Integrating an electrical storage to renewables is an effective solution depending on the round trip efficiency. The result presented in the last column of *Figure 4* correspond to the use of Li-Ion batteries that are the most efficient. Using Lead Acid batteries, CAES and Hydrogen storage, self-sufficiency achieve respectively 85%, 76% and 57%. The introduction of biogas largely improve performance. Cattle and goat can satisfy their entire demand using the electricity produced by biogas. Poultry and pig can satisfy between 30% and 40% of their demand using only biogas. What is lacking to equalize annual production and demand (N=1) is composed of Renewables.

The combination of Renewables and biogas permits them to achieve between 60 and 70% global satisfaction.

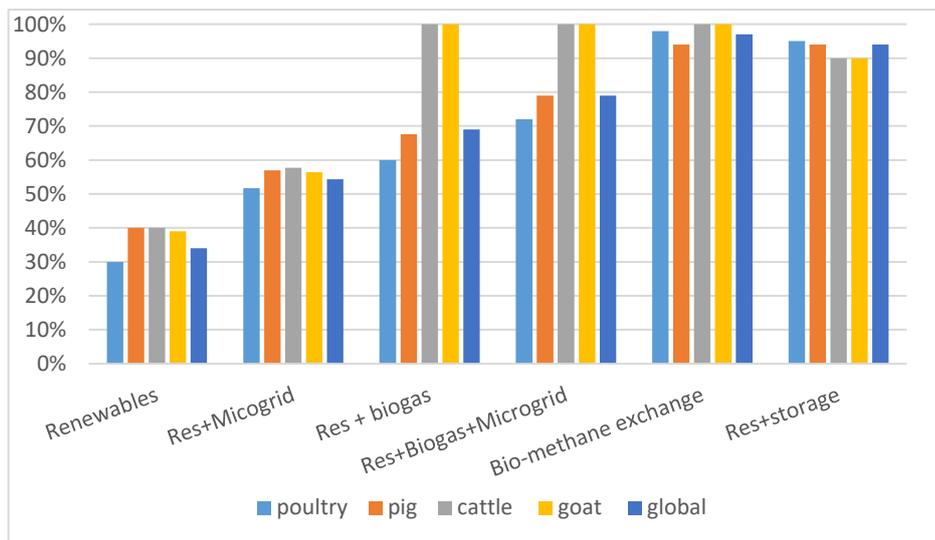


Figure 4 – resume of results, maximum energy demand satisfaction for different plant alternatives

The introduction of microgrids permits to increase global satisfaction up to 20%. Moreover, microgrids are essential to permit an effective biogas exchange. In the stand-alone case, cattle and goat consume almost all the biogas produced to satisfy their demand. Using a microgrid part of their demand is satisfied by renewables and they are able to save higher quantities of biogas useful for the exchange.

The level of satisfaction described in the fourth column of *Figure 4* reflects the case where biogas is exchanged through pipelines in form of bio-methane (biogas must

be always upgraded before to be exchanged). If pipelines are not available then the exchange is generally conducted using trucks in form of compressed bio-methane. Passing from one to eight truck exchanges is possible to improve global satisfaction from 79% to 94% (15% improvement). From eight truck exchanges to pipelines is possible to gain just an additional 3% of global satisfaction. This can be explained because the total amount of biogas available is fixed and the relative advantage reduces increasing the number of exchanges.

Farm internal conditions

As explained in chapter 2.2, the model gives the possibility to consider the impact of unfilled demand on the production process. Using appropriate equations (as equation 2.1) is possible to derive the evolution of temperature or relative humidity (R.H) inside the farm. Once known the relation between animals' efficiency and temperature, it is possible to evaluate the impact of resource scarcity. Moreover is possible to know the number of hours without refrigeration, lightning or other uses that compromise production. This study did not focus on this aspect of the model. An example is shown in chapter 4.9.

5. Economic analysis

- **Benefits:** avoided cost of electricity [0.15 €/kWh], avoided cost of methane [0.07 €/kWh], feed in tariff of each technology and subsidies for anaerobic digesters. (*Table 10 of the document*)
- **Costs power plant and storage system:** investment costs, O&M costs and replacement costs + additional plant costs to recover storage losses and storage losses cost.
- **Costs energy exchange:** see *Table 11 of the document*

Costs of electricity and methane is considered constant during the project lifetime. Discount rate (r) is 5% always. This value comes from ceicdata website [48] where is shown that in the last 30 years French discount rate have averaged around 5%. It is considered the same average in the next years. Project lifetime for NPC and LCOE calculation is 25 years always. No salvage considered.

Table 3 shows the most important economic considerations. Since different kind of scenarios are studied and all have negative performances, it is here directly presented the best performance obtainable among them. The LCOE of wind

turbines and PV panels is lower than the cost of electricity but since they are not able to satisfy more than 57 % of demand, they cannot recover the investment. Biogas has a higher LCOE in terms of electricity while lower in terms of methane respect to the national cost. Biogas electricity is more expensive than PV panels and wind turbines one, but demand satisfaction for some animal is 100%. Satisfying the entire demand biogas achieve better performances (lower NPC).

	<i>Minimum LCOE [€/kWh]</i>	<i>Minimum NPC [M€]</i>	<i>Maximum Benefits – Costs [k€/y]</i>
<i>Wind turbines</i>	0.137	0.035	X
<i>Photovoltaic</i>	0.122		X
<i>Biogas electricity</i>	0.195		X
<i>Bio-methane</i>	0.059	0.014	X
<i>Li-Ion battery</i>	8.6	1.72	X
<i>Lead Acid battery</i>	2.6	0.5	X
<i>.PEMFC storage</i>	0.72	0.177	X
<i>CAES</i>	0.55	0.11	X
<i>Energy exchange</i>	X	X	-13.72
<i>Energy exchange Without upgrading</i>	X	X	+3.08

Table 3– Resume of the economic results for each technology considered and for the energy exchange

The LCOE of the storage system shows that batteries are less suitable for this kind of applications. The huge cost difference between batteries and the other two technologies can be explained looking at the difference between the kW and the kWh size required by the storage system for its proper functioning. Batteries cannot take advantage of this disparity. Commercial batteries are characterized by low energy to power ratio (E/P) (max 0.5 h Li-Ion, max 10 h Lead Acid). In the renewable case of *Figure 4* due to the low matching supply-demand the E/P required range between 170 and 500 kWh/kW. The storage is characterized by small flows and large reservoirs that accumulates energy for weeks or months. Using batteries, cost will be high and their applications will bring to a complete underuse of these technologies.

On the contrary, CAES and PEMFC systems takes large advantage of this situation thanks to their higher E/P (respectively 160 and 840 h), they can largely reduce their power unit size and cost due to the low flow rates required.

This double advantage bring these two technology to be largely more competitive for this kind of applications. Their LCOE is between 4-12 times lower than batteries.

	<i>Batteries</i>	<i>PEMFC and CAES</i>
<i>Pros</i>	<ul style="list-style-type: none"> - Higher efficiency - Consolidated technology - Expected reduction of costs 	<ul style="list-style-type: none"> - High E/P that permits to largely reduce cost
<i>Cons</i>	<ul style="list-style-type: none"> - low E/P that reduce the adaptability of this technologies in this kind of application - Higher cost per kWh 	<ul style="list-style-type: none"> - Need still to penetrate the market - High cost of the power unit - Geologic dependence - Lower efficiency

Table 1 – Comparison between batteries, CAES and hydrogen storage

Anyway, no one of the considered technology achieve positive investments. *Table 2* shows that energy demand of poultry and pig is strongly characterized by heating. The direct use of current for heating increases the difficulties to find a solution based exclusively on renewables and storage for these animals. It is necessary to use biomethane to minimize the plant size. The use of Heat Pumps is another interesting solution that could be suggested to farmers. For energy exchange, the principal problem is related to the upgrading of biogas in bio-methane.

As it is possible to see in the last two rows of *Table 3*, without upgrading, the energy exchange has higher benefits than costs. Independently from the typology of exchange (trucks or pipelines), biogas must be depurated before to be exchanged and the cost of upgrading is generally affordable only for very large plants (100-350 Nm³/h). Here the biogas plants are farm-scale plants (3-5 Nm³/h) and is not possible to recover the investment. A suggestion to farmers could be to create a centralised biomass plant to cut cost of upgrading and maximize the amount of bio-methane produced combining manure with other bio-waste.

6. Conclusions

The model

The model demonstrated its capacity to simulate different scenarios and manage different technologies. Since it takes the principal characteristics of the system, part of resource demand and part of resource production as inputs, the accuracy of results is directly proportional to the accuracy of the inputs. Anyway, the formalization of reality in engines and the high number of agents and variables considered force the modeler to make simplifications and assumptions to describe reality. The combination of these two elements permits to the model to be suitable for pre-sizing and reasonable estimations. The principal weak point is the impossibility to perform an economic analysis and this could be a future development to improve its potentiality. Impact of resource scarcity is another important aspect for future development. In this study it has been shown the effective capacity of the model to reflect resource scarcity in variation of production efficiency but the analysis of the impact requires several considerations regarding probability of unfilled demand, thermodynamic of the system, humidity control, animals' behavior...etc. It is important to formalize the problem to find a good compromise between accuracy of results, complexity of the system and effective limits of the model. The adaptability to other productive systems as agriculture and fisheries is also an interesting future studies.

Case study

In general terms, what can be said is that while energetically is possible to achieve almost 100% self-sufficiency equalizing yearly production and demand ($N=1$), economically it is still a challenge. What principally limits positive investment is the non dispatchability of renewable sources, the still excessive cost of storage and the necessity of upgrading for biogas exchange. Reduction of costs and incentives that are more suitable will play a fundamental role to overpass the economical barrier still present. Units of energy internally produced or stored needs to be better remunerated to generate positive investments. Technological innovation and variety of solutions are also extremely important in these terms.

These kind of energy solutions today seem more adapted to rural contests devoid of national grid but the emerging policies, the always-lower cost of renewable solutions and world political instability could bring the centralized system to become less competitive in the next years.

Suggestions for improvement

- **Heat Pumps** Heat pumps today achieve COP between 4 and 6. With indicative costs that could vary between 200 and 1100 €/kW depending on the technology and application [49]. As a rough estimation, the use of heat pumps with COP = 4 in farms supplied only with electricity, would permit to reduce the size of the renewable plant from 225 kW to 60 kW for poultry and from 150kW to 94kW for pig. Energetically this is always a good solution while economically everything depends on the performance and cost of the heat pump. Another advantage of heat pumps is that they can be used also for cooling applications in summertime.
- **Pre-heating of air** If the external air used for internal air recirculation were pre-heated before to be introduced in the building, heating demand would reduce appreciably. Heat could be recovered by the anaerobic digester, CAES systems or inside air.
- **Incentives for self-sufficiency targets** The principal limit of the project stands on costs. Incentives for electricity stored or internally consumed for self-sufficiency targets could largely improve affordability.
- **Centralized Biogas production** Instead of producing in loco with small plants, all manure could be transported to a big plant and combined with other bio-waste to increase biogas yield. Farms characterized by electricity demand could be interconnected in a microgrid and supplied by biomethane turbines. The reduction of costs for upgrading and the higher quantities of biomethane generated will bring to cheaper and more effective exchanges. Total plant cost could reduce because of the economy of scale, but complexity and O&M costs will increase appreciably.

Sommario

Secondo gli obiettivi europei, al fine di ridurre le emissioni di gas serra e aumentare l'indipendenza energetica, la quota di energie rinnovabili nel mix energetico dovrebbe essere superiore al 27% nel 2030 e aumenterà negli anni fino all'obiettivo ambizioso di 80- Riduzione del 95 %% delle emissioni di gas serra rispetto ai livelli del 1990, entro il 2050. Gli studi riguardanti la possibilità di energia rinnovabile al 100% sono già stati condotti nei paesi europei.

Il sistema agro-produttivo giocherà un ruolo fondamentale in questi scenari grazie alla sua capacità di produrre bioenergia e biocarburanti. La rivoluzione energetica richiederà profondi cambiamenti nell'intero sistema elettrico, passando dalla generazione centralizzata a quella decentralizzata e distribuita con lo sviluppo continuo di nuove soluzioni. L'obiettivo generale di questo studio è la valutazione dell'impatto delle politiche energetiche e la gestione delle risorse per i sistemi produttivi nel settore agro-produttivo. In tutta Europa ci sono siti geografici dedicati alla produzione intensiva di animali. Grazie all'elevata densità di sfruttamento ottenibile e alla produzione di bioenergia, questi sistemi sono particolarmente interessanti. È importante disporre di strumenti che consentano di analizzare l'impatto delle energie rinnovabili e della generazione distribuita sul loro processo di produzione per sostenere il raggiungimento degli obiettivi europei. Poiché modelli adatti allo scopo di questo studio non sono disponibili in letteratura un modello adatto è stato concepito e sviluppato utilizzando Python 2.7, un linguaggio di programmazione open source.

In particolare, il modello è stato utilizzato per studiare la possibilità per pollame, bovini suini e caprini situati in Île-de-France (Francia), di essere energeticamente autosufficienti utilizzando energia rinnovabile, stoccaggio di energia, microreti e scambio di biometano. La domanda di energia considerata si concentra sui bisogni interni delle aziende agricole e non considera le esigenze indirette o correlate ai trasporti. L'obiettivo è capire quali sono le dimensioni minime dell'impianto richieste, i costi e la fattibilità del progetto.

Parole chiave: modello, modello di simulazione, gestione delle risorse, politiche energetiche, obiettivi europei, energie rinnovabili, stoccaggio di energia, bioenergia, sistema agro-produttivo, generazione distribuita e decentralizzata.

Abstract

According to the European targets, in order to reduce GHG emissions and to increase energy independence the share of renewable energy in the energy mix is expected to be higher than 27% in 2030 and will increase in the years up to the ambitious target of 80-95% reduction of GHG emissions when compared to 1990 levels, by 2050. Studies regarding the possibility of 100% renewable energy have been already conducted in the European countries.

The agro-productive system is going to play a fundamental role in these scenarios due to its capacity to produce Bioenergy and Biofuels. The energetic revolution will require profound changes in the whole electric system, passing from centralised to decentralised and distributed generation with continuous development of new solutions. The general objective of this study is energy policies impact evaluation and resource management for productive systems in the agro-productive sector. All around Europe there are geographical sites dedicated to intensive production of animal. Thanks to the high density of exploitations achievable and the production of bioenergy, these systems are particularly interesting. It is important to have tools that permit to analyse the impact of renewables and distributed generation on their production process to support the achievement of European targets.

Since models suitable for the purpose of this study are not available in literature (excluding not free of charge and elaborated software), a suitable model has been conceptualized and developed using Python 2.7, an open source programming language.

More specifically, the model has been used to study the possibility for poultry, pig, cattle and goat farms located in Île-de-France (France), to be energetically self-sufficient using renewable energy, energy storage, microgrids and bio-methane exchange. The considered energy demand focuses on the internal needs of the farms and does not consider indirect or related to transport requirements. The objective is to understand what is the minimum plant size required, costs, and affordability of the related project.

Keywords: Model, Simulation model, resource management, Energy policies, European targets, renewable energy, energy storage, Bioenergy, agro-productive system, distributed and decentralized generation.

1 Introduction

This chapter aims at providing an overview of the geo-political context of the study and the reasons behind its development. To define the model and compare it with other models present in literature. To briefly explain what are the general and the specific objective of the study and what is expected to turn out.

1.1 Renewable energy in European targets

The emerging policies aiming at reducing GHG emissions are always more promoting the introduction of renewable energy technologies, distributed energy resource deployment and technological innovation.

The attention focus also on the development of technological alternatives to achieve energy security and independence to meet the increasing energy demand. The European commission explain that The EU imports 54% of all the energy it consumes, at a cost of more than €1 billion per day. Energy also makes up more than 20% of total EU imports. Specifically, the EU imports:

- 90% of its crude oil
- 69% of its natural gas
- 42% of its coal and other solid fuels
- 40% of its uranium and other nuclear fuels.

Security of energy supply is an integral part of the European Union strategy. Energy supplies are exposed to risks that include disruption from countries from which the EU import fuel but also terrorism and hybrid threats.

Moreover, renewable energy is an economic opportunity. The European Union (EU) has long been worldwide leader in the promotion and development of renewable energy also because it is emerging as a driver of inclusive economic growth, creating jobs. To fulfil its aspiration to become the global leader in renewables, Europe will need to maintain a growing domestic market. The additional investments required to reach the 2020 and 2030 targets will help Europe to maintain its leading role while deriving substantial macroeconomic benefits in terms of growth and balance of trade, as well as creating a new industrial base around the renewables sector.

	<i>GHG emissions</i>	<i>Renewable Energy</i>	<i>Energy Efficiency</i>
Target 2020	-20%	≥20%	≥20%
Target 2030	-40%	≥27%	≥27%
Target 2050	- (80÷95%)	Increased	Increased

Table 2 - the EU 2020, 2030 and 2050 targets

Table 2 shows the actual European targets from here to 2050. Renewables are expected to increase always more in time together with efficiencies.

In the study “Renewable Energy Prospects for the European Union” conducted by IRENA (international Renewable Energy Agency) and the European commission, the vision is even more optimistic. The EU could double the renewable share in its energy mix, cost effectively, from 17% in 2015 to 34% in 2030.

Almost complete decarbonisation is expected in 2050. The European commission consider decarbonising the energy system technically and economically feasible. In the long run, all scenarios that achieve the emissions reduction target are cheaper than the continuation of current policies.

France

Numbers for France are in the range of the European target. The “Ministère de la transition écologique et solidaire” set the ambitious target of 32% renewable energy in 2030 using subsidies for renewable energy projects, tax reduction, tax credit and R&D funding. The same Ministry supported the study “A 100% renewable energy mix – analysis and optimization” conducted by ADEME (Agence de l'environnement et de la maîtrise de l'énergie) French environment and energy management agency. A very ambitious project that explains that a 100% renewable mix can be reached thanks to profound changes in the whole electric system. Distributed energy and network development is necessary and can pool the potential. Combination of technologies is crucial.

This kind of study shows the interest of the European countries to move to highest share possible of renewable energy quickly as possible for all the reasons explained.

1.2 The agro-productive system

The agro-productive system will play an important role in energy targets achievement and is an interesting object of study from different perspectives.

In terms of energy transition, the agro-productive contest (or rural contest) is very suitable. Agriculture and Livestock production is generally located distantly from populated areas and characterized by large spaces available. In these terms, the installation of renewable technologies becomes simpler and power production more performing. Think about eventual problem of shading related to near buildings, impossibility of correct orientation in photovoltaic installations, noise related to wind turbines operation, minimum distance between two wind turbines...etc.

The introduction of microgrids and distributed energy can be an effective solution especially considering intensive production, where the number of exploitations per km² becomes very high. Moreover, rural areas are generally characterized by lower services in terms of grid and inefficient energy systems, then, they could be more attracted by solutions based on autonomous or distributed renewable energy.

While the common agricultural policy does not provide direct financial support for the production of biomass for bioenergy, EU rural development policy includes measures aimed at encouraging the production and use of renewable energy. Through their rural development programmes, EU countries can introduce specific measures to support renewable energy such as investments in renewable energy production or consumption.

The great energy potential of the agro-productive system is contained in the Bioenergy. Bioenergy can be defined as the result of the conversion of biomass resources, such as trees, plants, agricultural/forest residues and urban waste, into energy and energy-carriers including heat, electricity and transport fuels.

Biofuels plays another important role in helping the EU meet its climate and energy objective. Biofuels are liquid or gaseous transport fuels such as biodiesel and bioethanol, which are made from biomass. They are considered as renewable alternative to fossil fuels in the EU's transport sector to reduce greenhouse emissions without adversely affecting the environment. For this reason, rigorous sustainability criteria are applied to biofuels producers.

By 2020, the EU aims to have 10% of the transport fuel of every European country come from renewable sources such as biofuels. This percentage is expected to grow in time.

To resume the agro-productive system has the advantage to simplify renewable installation and distributed energy solutions, contains in itself the great energy potential of Bioenergy that can be extracted from its waste to produce heat, electricity and fuels and will be an important supporter to achieve the European climate targets in the next years.

Out of the energetic contest, it is important to consider that the agro-productive system is at the base of the human production system, human surviving and well-being. Food and nutrition security is of primary importance in any country. It is crucial to study agriculture adaptability to new type of energy supply.

What would be the impact of the shift?

What limits the introduction of renewable technologies and distributed energy is generally related to costs and economic affordability. Even if farmers wish to be energetically self-sufficient and off-grid, they generally cannot afford the investment. For this reason, local governments and the EU support these kind of investments with subsidies, incentives, tax reduction and other instruments.

It is important to develop correct energy policies that promote the introduction of renewable technologies in rural contests together with positive investments.

What limits the affordability of the investments?

Suitable models to study agricultural energy transition

In order to answer to the present questions is important to have the right instruments.

The agro-productive system in fact is different to the other typical production sectors because its product is biological and alive. The study of energy and resource consumption requires taking into consideration the relation between living organisms and the external environment. Biological products are delicate especially in the yearly stages of life and lack of resources could bring to the complete collapse of production (death).

In these terms, the introduction of intermittent source of energy generates additional challenges and effective solutions can be found only using suitable models able to describe the relation existing between energy consumption, agricultural production and bioenergy production. At the same time, the affordability of investments is strictly related to the performance achievable. To compare the performance of the system in different conditions of access to energy and alternatives of production is essential to find a possible solution and suggestions for improvement.

1.3 Definition of the model

When talking about models, it is important to specify what kind of model is under consideration. Energy models (and, more generally, systems analysis models) can be divided into two categories: *simulation models* and *optimization models*.

- **Simulation models** attempt to provide a descriptive, quantitative illustration of energy demand and conversion based on exogenously determined drivers and technical data with the objective to model observed and expected decision-making that does not follow a cost-minimizing pattern.
- **Optimization models** try to define the optimal set of technology choices to achieve a specific target at minimized costs under certain constraints leaving prices and quantity demanded fixed in its equilibrium.

Moreover, models can be static or dynamic. A *static model* does not contain time as a variable and is, therefore, not able to simulate the behaviour of a system over time, as opposed to a *dynamic model*.

A more generic distinction stands between top-down and bottom up model. They can be either simulation or optimization models or either static or dynamic models.

- **Top-down energy models** try to depict the economy as a whole on a national or regional level and to assess the aggregated effects of energy and/or climate change policies in monetary units. In contrast to bottom-up modelling, these equation based models take an aggregated view of the energy sectors and the economy when simulating economic development, related energy demand and energy supply, and employment.
- **Bottom-up energy model** are characterized by relatively high degree of technological detail (compared to top-down energy models) used to assess future energy demand and supply. In contrast to top-down models, bottom-up models use a business economics approach for the economic evaluation of the technologies simulated. They usually cannot consider macroeconomic impacts of energy or climate policies or related investments. They do not consider transaction costs, which are implicitly covered by top-down models.

Finally, a distinction is made on the geographic extension of the system (*local, regional, national or global*) and the level of economic characterisation (*technical-economical models, macro economical models*).

As definition, the model is a *Dynamic Simulation model* based on a *bottom-up approach* suitable for *local applications* (but adaptable to *regional*) and *techno-economic analysis*. Taking resource production and demand as inputs, the model aims to simulate resources consumption, conversion, recycling and storage. Using exogenous relations set by the user, it gives also the possibility to describe the impact of resource scarcity on the system and how the system influence the inputs.

1.4 Literature review and models comparison

Literature present different typical solutions for agricultural simulation and optimization. Feola, Sattler and Saysel [50] listed the principal one. In particular:

- **Linear programming (LP)** is a mathematical method of determining a way to achieve an objective with a given or limited set of resources. The expression to be maximized or minimized is called the objective function. The optimization of the objective function is subject to linear equality and inequality constraints. LP is an effective solution to find the optimal mix that minimize cost or the best technological mix (e.g. Camarena et al. 2004) [51]. It permits to interrelate energy and farms but does not permit to describe the internal dynamics and evolution of the system.
- **Agent-based models (AMB)** are computational models representing a population of interacting agents situated on a virtual landscape or environment. They are studied principally to understand the interaction and relative influence between agents for the adoption of new technologies or reaction to new policies (e.g. Deffuant et al. 2001) [52]. They can be implemented for parallel studies but they are not suitable for the targets of this model.
- **System dynamics (SD)** modelling and simulation aim at improving our understanding of the root causes (structure) and trajectories (behaviour) of dynamically complex problems. SD research cycle starts with *closed-loop* dynamic problem identification. Closed loop dynamic problems are characterized by change over time, which cannot be trivially explained by exogenous driving factors. The *model structure* is developed by identifying

the stocks, flows (change in stocks), delays (the time lag between cause and effect) and nonlinearities (un-proportional, nonlinear influence of stocks on flows). System dynamics is the model most nearer to the developed one. Alam, Bala and Huq [53] used it to simulate rural energy systems for farming in Bangladesh. Mutingi, Mbohwa and Kommula [7] suggest the use of SD for energy policies simulation and modelling. SD is very suitable for studying internal dynamics of the system but is not a compact model to describe the production process in its linearity. Formal simulation model is typically a non-linear system of differential equations while linear equations and simple relations characterize the system here.

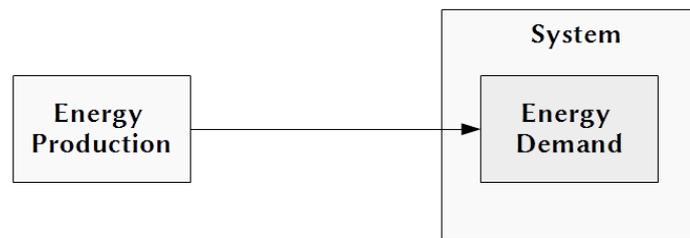
Literature presents several simulators for farms (e.g. CAPRI and X-farm [2],[3]). They are generally based on input-output approaches but the attention focus more on the agricultural aspect. Energy is considered an input necessary for the proper functioning of the system and is simply accounted. The study of correct renewable solutions in the agro-productive sector cannot be reduced to a simple accounting of energy demand. It requires the development of dynamic simulations that show the matching between supply and demand, the use of storage systems and biogas production as by-product of the production process. Frisk [4], for the simulation and optimization of a hybrid renewable energy system for farms located in Cuba, develops a methodology to estimate farms energy demand and biogas production from manure but they are used as inputs for a famous microgrid software called HOMER [5]. This solution is effective but does not permit to have a compact and reproducible approach. Herbst et al. [6], list the principal energy system models used today.

The first category represent simulation models used to size the power plant or to simulate power production. They describe in details the technology (photovoltaic panels, wind turbines, anaerobic digesters...) but they do not give the possibility to interrelate production with an external economy or the production process of the considered sector (e.g. Transys). In this category can be included also models for microgrid simulations.

Cong, Cahill and Menzel [8] made an analysis of energy simulation tools in the building environment. Taking as input geometry, HVAC systems, weather conditions, internal loads, and number of loads... they describe energy demand using a set of parameters and equations characterizing the system (e.g. Simergy). Even if highly detailed, these models represent "passive" energy loads and cannot describe the dynamics of the production process inside the building.

The last category regards “macro-economic energy models”. They look at economy as a whole on a national or regional level and assess the aggregated effects of energy and/or climate change policies in monetary units. Examples are input-output models, World Energy Model (WEM) or MERGE, input-output models. These models permit to analyze the relation between energy and several other sectors, but they generally describe any process with black boxes characterized by input and output flows that largely reduce the level of details to describe the single process.

Typical approach of energy modelling



Approach proposed in this study

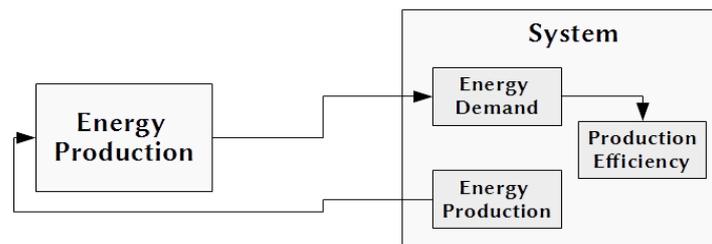


Figure 1 - Typical energy modelling approach versus approach proposed in this study

The model is not directly comparable with the first and the second category because is not able to simulate energy demand and energy production (they are exogenous inputs). The approach is similar to the macroeconomic one but focus more on the single sector or several sub-sectors that characterize a local economy. Reducing geographic extension and complexity of the system (number of sectors interacting) is possible to increase the level of details for the single production process. As the macroeconomic ones, the model is compact and use a general approach that is adaptable to different systems. It is not strictly related to the subject simulated, but this reduce at the same time its capacity to simulate technologies in details. Models similar to the one presented have not been found in literature, and then it is not possible to give a direct example.

Figure 1 graphically resume the evolution of the approach proposed in this study for energy modelling.

The voice Energy Demand is drawn inside System to explain that the characteristics of the system typify demand. The simulation model can be more or less precise describing these characteristics. Energy production is outside the system boundary because the attention focus on simulation models where the system is the load. In this study, a simple description of Energy Demand is not sufficient (even if highly detailed) to size the power plant. The agro-productive system is a potential energy producer (Bioenergy) and must be considered the possibility to internally produce energy. Moreover, the system is supposed to work with intermittent source of energy that could generate incomplete satisfaction of Energy Demand and damage production efficiency. It is important to account the effects of incomplete satisfaction in order to know the limit conditions acceptable.

Since the load is representing a production process, which is something dynamic by its nature, the energy demand can be largely influenced by the intensity of production at which the system is working. The production process could generate some by-product that directly affects energy demand and this influence will be directly proportional to the production intensity.

All these considerations arise because the present model has not as unique objective to be an energy simulator. It has a multidimensional intention and is principally interested in the relation between the energy sector and other sectors, and not exclusively in the energy sector.

How the model performs the logic and the working principle described is explained in details in chapter 2, here it is just described in general terms to highlight the differences with other models.

	<i>Farm models</i>	<i>Energy models</i>	<i>Developed model</i>
<i>Pros</i>	<ul style="list-style-type: none"> • Higher level of details in terms of farm's internal dynamics-evolution, interaction between agents and direct-indirect requirements • Possibility of optimization 	<ul style="list-style-type: none"> • Possibility to directly analyse the impact of energy policies on the economy • Easier adaptability to global or national perspectives • Possibility of optimization 	<ul style="list-style-type: none"> • Higher relation between energy and characteristics of the system • Interrelation between sector efficiency and energy demand satisfaction • Possibility to consider the system either producer or consumer of energy
<i>Cons</i>	<ul style="list-style-type: none"> • Lower relations between energy and the production process. • Lower interest on the energetic characteristics of the system 	<ul style="list-style-type: none"> • Lower interest in the single sector dynamics • Lower interest in the relation between energy demand satisfaction and sector's internal dynamics 	<ul style="list-style-type: none"> • No optimization performable • Lower possibility to describe farms in details • Lower adaptability to global/national contests • No possibility to directly analyse the impact on the economy

Table 3 - Comparison between farm models, energy models and developed model

Finally, *Table 2* gives a resume of what explained in this chapter, highlighting the principal pros and cons between the developed model and what could be easily found in literature.

1.5 Objectives and expected results

As introduced in chapters 1.1 and 1.2, the UE and national energy targets aims to increase always more the share of renewable technologies in their energy mix to reduce GHG emissions, dependence from other countries and increase energy security. Due to their nature, renewables technologies introduction implies a profound change in the whole electric system, promoting the development and use of distributed and decentralised generation.

The general objective of this study is energy policies impact evaluation and resource management for productive systems in the agro-productive sector. All around Europe there are geographical site dedicated to intensive production of animal and vegetable products. In Bretagne (France) for example, is possible to find 16 or more exploitations in 10 km² [9]. For all reasons explained in chapter 1.2 and thanks to the high density of exploitations achievable, these systems are particularly interest. It is important to have tools that permit to analyse the impact of renewables and distributed generation on their production process to support the achievement of European targets and reduce GHG emissions of the agro-productive sector, which is among the principal responsible [10].

Since models suitable for the purpose of this study are not available in literature (excluding not free of charge and elaborated software as HOMER), a suitable model have been conceptualized and developed using Python 2.7, an open source programming language.

More specifically, the model have been used to study the possibility for poultry, pig cattle and goat farms located in Île-de-France (France), to be energetically self-sufficient using renewable energy, energy storage, microgrids and bio-methane exchange. The considered energy demand focus on the internal needs of the farms and does not consider indirect or related to transport requirements. The objective is to understand what is the minimum plant size required, costs, and affordability of the related project.

2 Model and methods

This chapter aims at describing the working principal of the model, its components and its architecture. How the model describes and formalizes reality. The principle equations that govern the system and its inputs, and the logic used to simulate energy exchange. Finally will be described the instruments used to perform the economic analysis.

2.1 Introduction to model and methods

Simulation models attempt to provide a descriptive, quantitative illustration of resource demand and conversion based on exogenously determined drivers and technical data with the objective to model observed and expected decision-making that does not follow a cost minimising pattern.

This model in particular has as objectives:

- To simulate livestock and production of animal products.
- To estimate energy consumption related to livestock production
- To estimate production of biogas using animal bio-waste
- To evaluate the influence of animals characteristics on energy demand
- To evaluate the effects of partial satisfaction of energy demand
- To evaluate the effects of energy exchange between farms

In order to be well structured, the model cannot look directly at the specific object (livestock in this case). A general basic logic that looks at resources in a more abstract sense must be developed and then adapted to the specific objective.

The introduction will follow describing the basic logic of the model and its inspirers. First chapters of methodology aims to explain how real animals have been adapted to the model, the model structure and the working principle to simulate production, consumption and exchange of resources.

Last chapters describes the criteria used to size energy demand and production and how to develop an economic analysis for an estimation of the economic affordability of results.

2.1.1 Conceptual map

A coloured conceptual map is here presented to give a compact and global description of the model and its exogenous drivers.

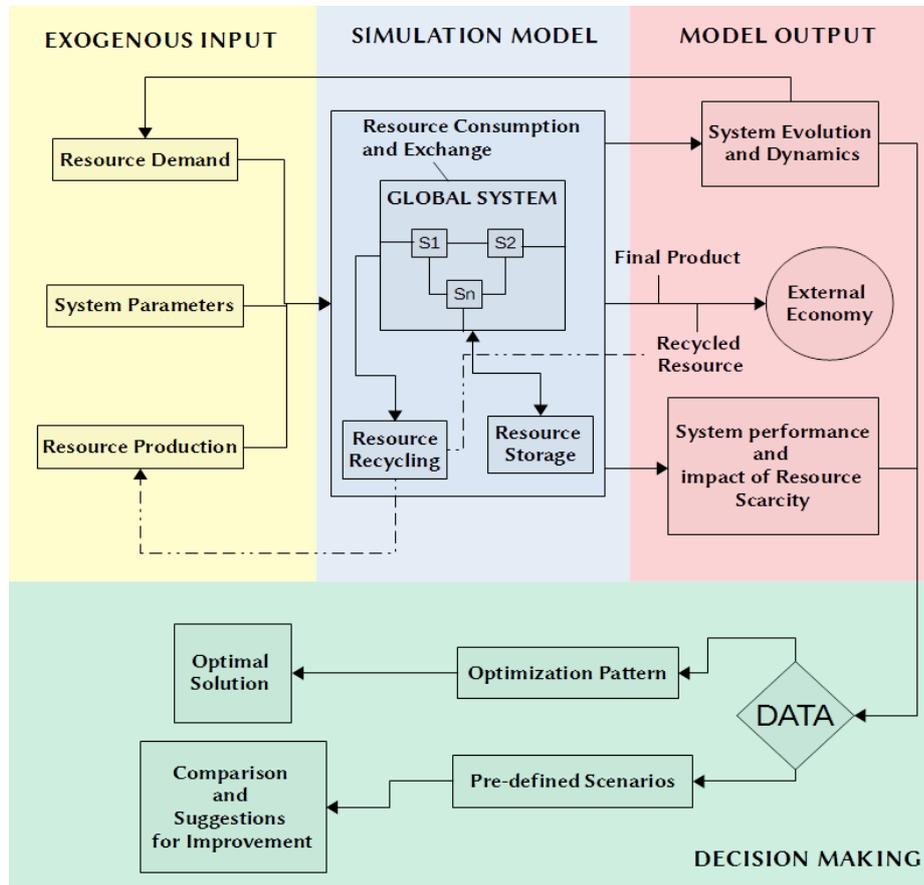


Figure 2 – Introductory conceptual map of the model working principle.

- **The yellow region** describes the principal exogenous inputs of the model. In particular, they are demand and production of any resource considered and the parameters characterising the system. [More details in chapter 3 for all parameters and their calibration while chapters 2.7 and 2.8 describe the methodology used to develop demand and production]
- **The blue region** describes in general terms the simulation model. The model is dynamic, meaning that describes the evolution of the system in time. Using exogenous inputs, it simulate consumption, storage and recycling of resources. S1, S2 and Sn stand for “system”. If the global system

is composed of n systems (or sub-systems), than it is considered the possibility to exchange resources between them. Recycled resources can be internally consumed to support exogenous production or sent to an external economy as final product. . [More details from chapter 3.2 to chapter 3.5]

- **The red region** represent model output. Final Product can be considered the “physical output”, directly related to the production process. “System Evolution and Dynamics” is directly connected to “Resource Demand” because the model take into consideration how system dynamics influence input requirements [chapter **Error! Reference source not found.**]. Finally, the model gives information about system performance and impact of resource scarcity in different scenarios. [More details in chapter 4]

- **The green region** explain how the simulation model can be used for decision-making.

An optimization model determines the optimum solution given the objective function and restrictions, whereas a simulation model calculates the outcome of predefined sets of variables.

If the objective of the user is to find an optimal solution, the model will give data but the optimization must be performed using an exogenous optimization pattern.

If the objective of the user is to compare pre-determined choices, than will be sufficient to run the simulator in all configurations.

In this study, the attention focused on this second solution since the objective is to show the potentiality of the simulation model. [More details in chapter 5]

2.1.2 Material Flow Analysis as rationale

By definition, material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time. Because of the law of the conservation of matter, a simple material balance comparing all inputs, stocks, and outputs of a process can control the results of an MFA. It is this distinct characteristic of MFA that makes the method attractive as a decision-support tool in resource management, waste management, and environmental management.

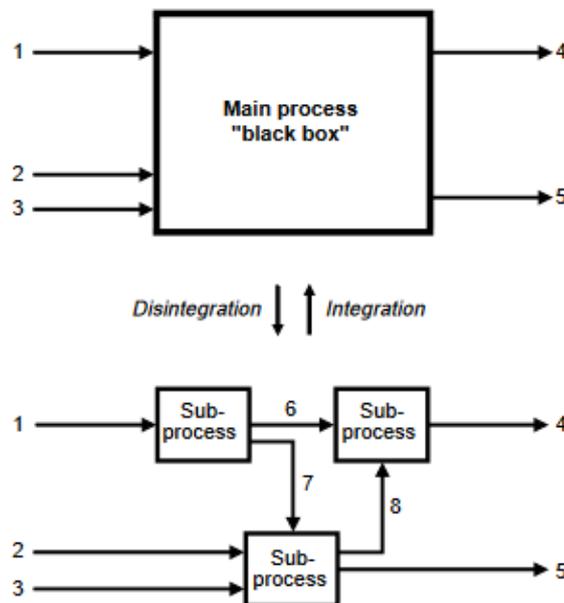


Figure 3- Opening up a black box by subdividing a single process into several sub-processes provides additional information about the black box.

Principal scope of the presented model is resource management and waste management. Due to its simplicity and compact results control, the MFA becomes a useful instrument to structure the basic logic of the model [11].

Everything is based on an input-output approach where input flows are converted inside the black box in output flows. Output flows could represent useful products or waste. It is also considered the possibility for any process to store or recycle resources. The black box representing the main process can be split in several sub-processes in order to provide additional information (Figure 3).

Looking at the main process as system boundary, the sub-process can produce for either an exogenous demand (flows 4 and 5) or just to support endogenous production (flows 6 and 7).

At the same time, the MFA permits to analyse the correctness and coherence of results. According to the mass-balance principle, the mass of all inputs into a process equals the mass of all outputs of this process plus a storage term that considers accumulation or depletion of materials in the process.

$$\sum_i^N \mathbf{m}_{in} = \sum_i^M \mathbf{m}_{out} + \mathbf{m}_{storage} \quad (2.1)$$

In equation 2.1, N is the total number of input flow (e.g. flows 1, 2 and 3 of the main process) while M is the total number of output flow (e.g. flows 4 and 5). The balance applies to the single process/ sub-process as well as the entire system. If inputs and outputs do not balance, one or several flows are either missing or they have been determined erroneously. A true material balance of a process or system is only achieved if all input and output flows are known, and if either $m_{storage} = 0$ or $m_{storage}$ can be measured.

2.1.3 From black box to engine

MFA is the basis for modelling resource consumption as well as changes in stocks but the simplicity of the approach reduces the level of details extractable. Resource and waste management is not the only objective of the present model. It aims to describe the evolution of the system more in detail. To evaluate the impact of resource scarcity on productivity, the influence of process dynamics on the inputs, the efficiency of the storage and others, difficult to describe simply using the MFA.

It is evident that the level of details required by the simulation model is proportional to the complexity of the model itself. In these terms, the simple use of “black boxes” to describe processes is not more exhaustive.

The engine of *Figure 4* is the central element of this model and characterize any production process. It derives its theoretical bases from the work of Louis-*napoléon* , Giraud, Herbert et al. [12] that looks at macroeconomic dynamics as thermodynamic engines and from the basic concept of input-output analysis [13]. *IP* represent the intensity of production while η is the efficiency at which resources are converted in final products. *IP* and η are variables not parameters and could vary if influenced by exogenous factors.

Resources are extracted from the stock of primary resources *XH* or come directly from an exogenous supply. The waste is directed to the stock of waste *XL*. Demand is the motor that generally drives the engine but it could work also with lower or

higher intensities. In that case, the storage of final products helps the engine absorbing or giving final products. Π_H and Π_L are arbitrary transfer functions that can describes exogenous influences on the production process.

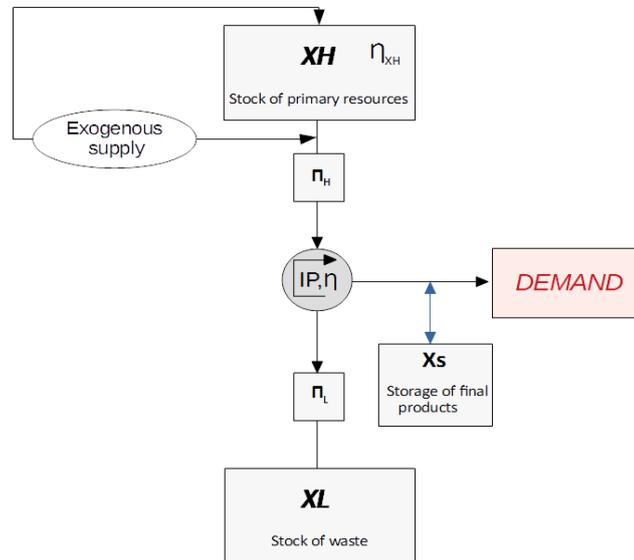


Figure 4 – The engine

The advantages derived using engines are:

- It is possible to study at the same time the storage of both inputs and outputs
- To take into account inefficiencies in the storage process
- To quantify resources, waste and final products available
- To describe internal dynamics of the production process expressed as variation of efficiency or intensity of production.
- To evaluate dependency of production from the exogenous supply of resources. How much time production can last without relations with the external world.
- The use of arbitrary transfer functions to connect the engine to the stocks permits to analyse resistances and delays of the system that are not directly connected with the engine's proper functioning.

NOTE: More details about engines and their application can be found in chapter 2.3

2.1.4 System dynamics

As introduced in the conceptual map and in the engine presentation, the objective of the model does not focus exclusively in the accounting of resource consumption. System dynamics, evolution and responsiveness to altered conditions are also essential information.

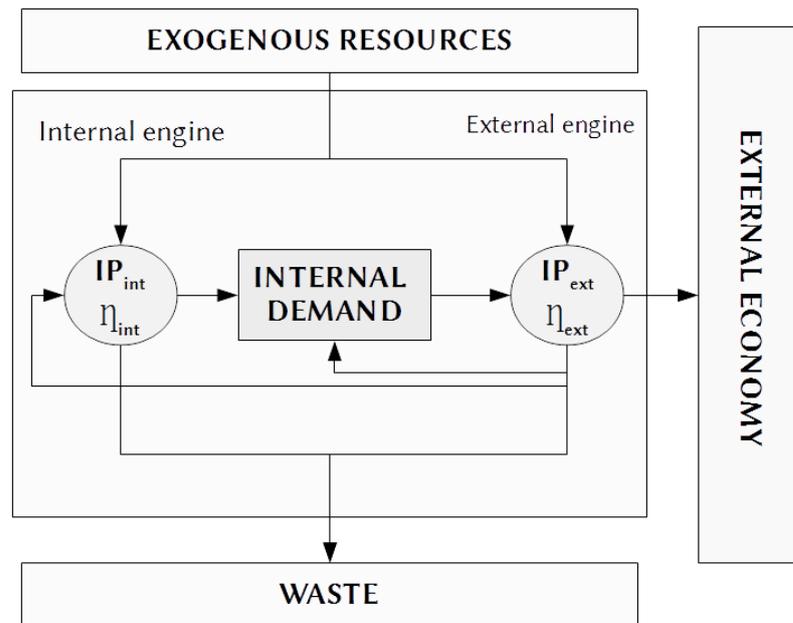


Figure 5 – Causality logic and feedback flows used to analyse system dynamics

Figure 5 explain how the model aims to describe system internal dynamics while accounting resource consumption.

A production process generally uses more than one resource to generate useful products. Anyway, not all resources used are converted in final products directed to an external economy. Some resource could be simply used for the proper functioning of the system. Energy is a very good example.

The internal engine represent the internal uses of the production process, its product is directed to satisfy the internal demand. The external engine represent the production process, its product is directed to an external economy. The two engines are identical, they simply differ in terms of demand and what they represent.

A causality chain is used to describe the impact of resource scarcity. The internal engine try to satisfy the internal demand using exogenous resources. If there are not sufficient resources, the internal demand will not be satisfied. If the internal

demand is not satisfied, the efficiency or the intensity of production of the external engine (IP_{ext} , η_{ext}) reduces. At the same time, the external engine could generate by-products usable to run the internal engine or vary the internal demand.

The same reasoning is valid also between internal engines, they could influence each other.

To resume, describing the production process, it is important to distinguish which are the external and which are the internal engines. Then must be set the relation existing between internal demand, external engine and internal engine. Using a given set of equations, the model describes the evolution of the system and accounts for resource consumption.

The concept is similar to the one described in *Figure 3* while describing the material flow analysis. Looking at the entire system (main process), it is possible just to see a set of exogenous resources converted in final products and directed to an external economy. Disintegrating the system is possible to enter in the details of the internal processes. Respect to the black boxes of the MFA, the engines permit to describe also the internal dynamics of the system thanks to causality chains and feedback flows. In this terms the model recall the logic of System Dynamics (SD) described in chapter 1.4.

An example can be made using poultry's farms and energy. Chickens produce meat or eggs at maximum efficiency only if the internal temperature of the shed is at desired levels. If there is not sufficient energy to heat up the shed probably, temperature will be lower.

If the temperature is lower than the desired one, chickens will produce with efficiency lower than the optimal one. At the same time, chickens eat to survive and produce. Part of the energy contained in their feed is converted in heat and manure. Heat influence demand of heating and cooling, manure can be converted in biogas that can be used to produce heat.

Energy and animals feed are the exogenous resources. The heating system is the internal engine that converts energy in heat to satisfy internal heating demand. Chickens are the external engine, their product is directed to an external economy, their efficiency is related to the proper functioning of the heating system and they influence heating production and demand. Temperature represent the relation between the internal and the external engine or between internal demand satisfaction and the external engine.

Note: This example is extrapolated from the case study that will be presented in chapter 3.

2.2 Animals as engine

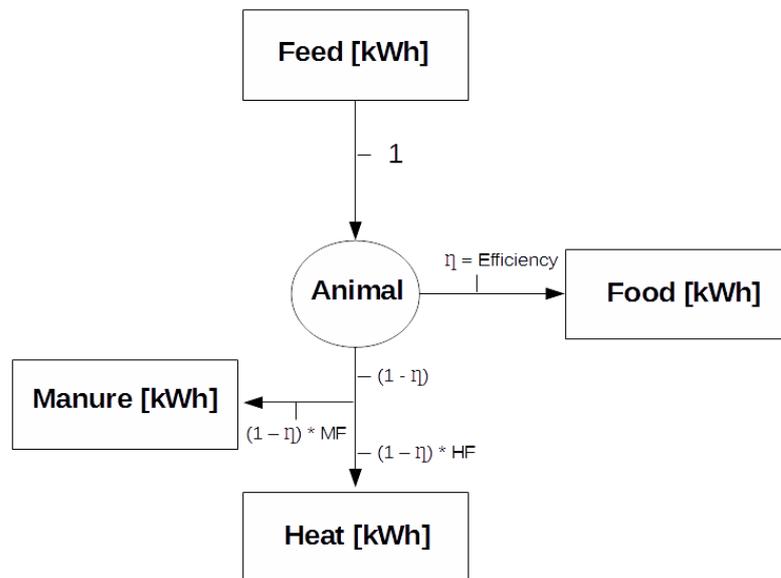


Figure 6 - Engine Animal

In order to adapt to the model, any animal is modelled as an engine that convert the energy contained in its feed in another form of energy, food. What is left of the efficiency is shared between manure and heat, which can be considered the waste of the production process. Conversion efficiency is not parameter. It is function of the conditions inside the farm. If the inside conditions are at desired values, efficiency is maximum otherwise reduces.

Figure 6 gives a graphical resume of what already explained. The levels of dry matter feed intake are calculated as share of the AAW (DMF) and converted in kWh thanks to the feed conversion factor (FCF). In formulas:

$$FIE = AAW \times DMF \times FCF \quad (2.2)$$

$$FE = FIE \times \eta \quad (2.3)$$

$$ME = FIE \times (1 - \eta) \times MF \quad (2.4)$$

$$H = FIE \times (1 - \eta) \times HF \quad (2.5)$$

FIE = Feed Intake Energy [$\frac{kWh}{day\ animal}$], energy contained in the animal's food

AAW = Average Animal Weight [kg]

DMF = Dry Matter Fraction [%],

FCF = Feed Conversion Factor [$\frac{kWh}{kg_{FI}}$], kg_{FI} = kg feed intake

FE = Food Energy [$\frac{kWh}{day\ animal}$], energy contained in meat, eggs and milk

η = Animal efficiency [dimensionless]

ME = Manure Energy [$\frac{kWh}{day\ animal}$], energy contained in the animal's manure

MF = Manure Fraction [%]

H = Heat released by the animal [$\frac{kWh}{day\ animal}$]

HF = Heat Fraction [%]

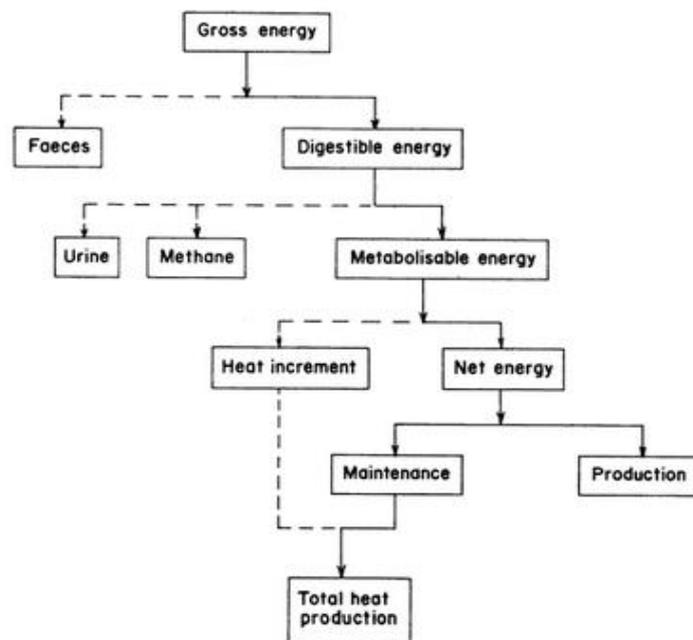


Figure 7 – The partition of feed energy in an animal

At the actual state is not possible to find in literature models that consider animals as engine. A similar approach is presented by Chatzimpiros and Harchaouoi in [16] reconstructing the production efficiency of French Livestock using the energy contained in their feed as input.

Anyway, animals as engines is not an absurdity. FAO (Food and Agriculture Organization of the United Nations) describes in the document "Food energy-methods of analysis and conversion" [14] the principal energy conversion related to animals' metabolism, resumed here in the flow diagram of *Figure 7*.

Starting from the gross energy (GE) contained in their feed, animals derive the net energy (NE), useful for their production and maintenance, excluding the energy contained in feces, methane, urine and total heat production. The engine efficiency represent the fraction of NE devoted to production. Compared to the typical approach the engine resumes everything in three principal outputs (production, heat and manure).

Everything is expressed in energy units because, considering the farm, while food is produced to satisfy an exogenous demand, heat and manure influence respectively endogenous energy consumption and production. Energy is in fact the second resource analysed in the model. Heat influence demand of heating and cooling, manure can be converted in biogas. With everything expressed in energy units, the accounting of such influence is simpler.

2.3 Energy engine

The energy engine represents all the typical energy uses related to a production process (ventilators, heaters, pumps, machines...etc.). It use energy in form of electricity, natural gas or other fuels to produce useful products as heating, cooling air ventilation, lightning...etc. Even if in reality, the efficiency of these engines can vary with the intensity of production (think about an electrical motor); here they are simplified with constant efficiency. This simplification is a forced condition to simplify the structure of the model and to have a general and simple approach valid for all the engines considered. This does not mean that any engine works with single intensity IP. The model differentiate engines that work with variable intensity or constant intensity, but *the efficiency is not function of the intensity of production*.

2.4 Model structure

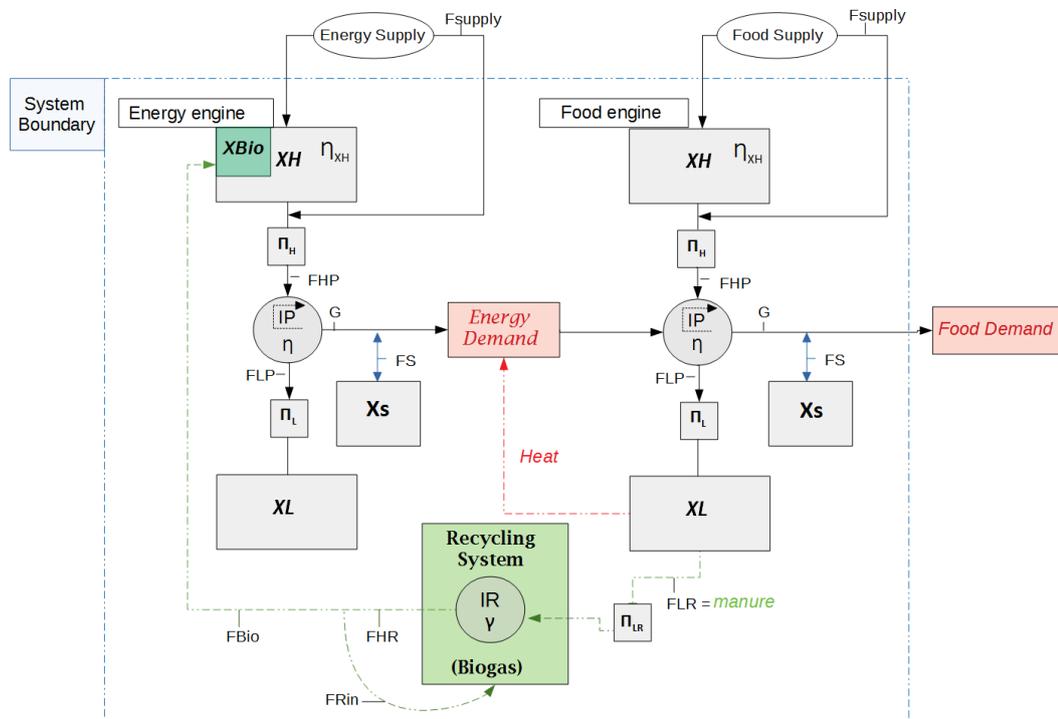


Figure 8 – Model structure

The model take as input:

- **Energy Demand**, . It is related to the endogenous needs of the farm.
- **Food Demand**, it depends on the exogenous needs of the considered economy.
- **Fsupply** = Flux of exogenous supply of resources. It could be directly used by the engine or going in the stock XH and be netted of its efficiency (η_{XH}).
- **IP** = Intensity of production. Demand driven or arbitrary set.
- **IR** = Intensity of recycling.
- γ = Recycling conversion efficiency
- η = Engine efficiency. ($\eta \in [0,1]$)
- η_{XH} is the efficiency of the “stock of primary resources”. It describes the fraction of resources lost in XH. ($\eta_{XH} \in [0,1]$)

- Π_H , Π_L and Π_{LR} = arbitrary transfer functions that relates stocks with engines. In this case: $\Pi_H = 1$ when $X_H > 0$ and $\Pi_H = 0$ when $X_H = 0$. $\Pi_L = 1$ always. $\Pi_{LR} = 1$ when $X_L > 0$ and $\Pi_{LR} = 0$ when $X_L = 0$.

The model gives as output:

- The “stock of primary resources” X_H , which is filled up by an exogenous supply.
- The “stock of waste” X_L
- The “storage of final products” X_s , which is filled up when production exceed demand or (if full) helps production when not sufficient to satisfy demand (the double arrow in the figure stands for this concept).
- X_{Bio} is the fraction of the “ X_H energy” reserved to biogas. Since electricity and biogas are not equivalent forms of energy, it is preferable to distinguish them.
- The intensity of production (IP) at which the engine is working to satisfy “Demand” any time-step.
- **FHP** Flux of primary resources necessary to satisfy demand.
- **FLP** Flux of waste
- **G** Flux of final product directed to satisfy demand.
- **Fs** Flux to/from the storage
- **FLR** Flux of waste directed to recycling / **Manure** generated by food engine as sub-product.
- **FHR** Flux of recycled resources
- The flux of Biogas **FBio** generated by the recycling system from manure
- **FRin** = flux of recycled resources internally consumed by the Recycling system. YR represent the fraction of FHR internally consumed [percentage].

The model is dynamic - all inputs and outputs of the system are function of time

As it is possible to see in *Figure 8* the structure of the model is based on the engine described in chapter 2.1.3, here called food engine and energy engine. They represent a typical machine as ventilators, heaters, pumps... used to satisfy endogenous requirements of the farm (energy engine) or the production process of the animals (food engine). The food engine is the animal engine of chapter 2.2 multiplied by the total number of animals in the farm.

The model is the combination of the single parts described in chapters 2.1.2, 2.1.3 and 2.1.4.

The principal equations of the engine are:

$$\mathbf{IP} = \frac{\mathbf{Demand}}{\eta} \quad (2.6)$$

$$\mathbf{FHP} = \mathbf{IP} \times (\Pi_H) \quad (2.7)$$

$$\mathbf{FLP} = (1 - \eta) \times \mathbf{FHP} \times (\Pi_L) \quad (2.8)$$

$$\mathbf{G} = \mathbf{FHP} - \mathbf{FLP} \quad (2.9)$$

The principal equations of the recycling system are:

$$\mathbf{FLR} = (\Pi_{LR}) \times \mathbf{IR} \quad (2.10)$$

$$\mathbf{FHR} = \gamma \times \mathbf{FLR} \quad (2.11)$$

$$\mathbf{FR}_m = \mathbf{YR} \times \mathbf{FHR} \quad (2.12)$$

YR represent the fraction of FHR self-consumed by the recycling system.

Excursus on Π_H , Π_L and Π_{LR}

As introduced, Π_H , Π_L and Π_{LR} are arbitrary functions that can be used to study the non-linearity of the production process. They are in parenthesis because they are used just if it is considered some exogenous influence that affects the performance. There are inefficiencies in the production process that are not directly expressible as variation of the efficiency. For example, suppose inefficiencies in the process of resource transfer from XH to the engine. These inefficiencies can be expressed setting Π_H lower than one (e.g. $\Pi_H = 0.9$). At parity of efficiency, if FHP is lower than IP; G will be lower than Demand (see equations 2.6 ÷ 2.9). It is not correct to express this reduction in terms of efficiency, because a reduction of the efficiency implies an increasing in the waste produced and this is not what happens in this case. Similar considerations can be made for Π_L and Π_{LR} .

$$\mathbf{G} = \mathbf{IP} \times \Pi_H \times (1 - (1 - \eta) \times \Pi_L), \quad \mathbf{s.t.} \quad \mathbf{G} \geq \mathbf{0} \quad (2.13)$$

Equation (2.13) shows in details how Π_H and Π_L influence production. It is clear that G must be always positive because a negative production has no coherence (same considerations are valid for FLR and Π_{LR}). This means that Π_H and Π_L must be carefully set to avoid errors. If Π_H and Π_L are equal to one, equation (2.13) becomes equation (2.9) and everything turns linear.

No longer speeches are made on the Π s because this study did not focus on the description of these kind of inefficiencies. They are presented as possibility of the model of extending the number of scenarios describable and representing reality.

In order to satisfy its demand, any engine works with certain intensity of production (IP). Equation 2.6 shows the case where IP is demand driven but It could be also independent from the demand.

In order to produce the flux of final products G , depending on efficiency, the engine extracts an amount of resources FHP from XH and generates an amount of waste FLP directed to XL . If there are sufficient resources, FHP is equal to IP and G is equal to Demand. If there are not sufficient resources, FHP is lower than IP and G is lower than Demand (see equations 2.6 ÷ 2.9).

The recycling system working principle is the opposite of the engine one. In order to produce the flux of recycled resources FHR , depending on conversion efficiency (γ), the recycling system extracts an amount of waste FLR and consumes an amount of resources equal to FR_{in} (see equations 2.10 ÷ 2.12). Notice that here there is only one arbitrary transfer function because the stock of primary resources where FHR is directed does not correspond to the stock of waste of the same resource and this could generate confusion. Moreover, FHR is not waste but the useful product and, as for engines, does not present any Π .

A reciprocal influence exist between the two engines, in fact, satisfaction of energy demand influence directly food engine's efficiency since is energy that permit to keep desired conditions inside the farm. At the same time, the food engine produces heat and manure as waste. The first influence directly energy demand, the second can generate additional units of primary energy, which can be stored or directly consumed.

The reciprocity between the two engines becomes a compact and efficient method to study the adaptability of the agro-productive system to different access to energy, the internal dynamics and to evaluate the effects of different choices (exploiting all the biogas available or partially, having more or less animals inside the livestock, using renewable technologies...etc.).

Since energy demand, energy production and the relation between energy and animals' efficiency are all exogenous input for the model, the accuracy of results will be directly proportional to the accuracy of the inputs

It is important to clarify that the engines are not thermodynamic engines. ΠH and ΠL are arbitrary transfer functions, not potentials (even if they could behave as potentials). Same concept is valid for the recycling system, it is in analogy with a heat pump but effectively it does not work as a heat pump. Analogy between thermodynamic and resources consumption in economies are well described in [12]. Here there is a free choice. Any resource can be modelled as most congenial.

Mass and energy balance in the model

For any resource (then for any engine), the following check is required any time-step. Considering as system boundaries the engine and the three stocks related to the engine (XH, XL and Xs).

$$XT(t) = XH(t) + XL(t) + Xs(t) \quad (2.14)$$

$$\sum_{i=0}^N Rin_i(t) = \sum_{j=0}^M Rout_j(t) + (XT(t) - XT(t-1)) \quad (2.15)$$

Rin = flux of the considered resource entering the system (Fsupply, FBio...)

Rout = flux of the considered resource exiting the system (G, FLR, Heat...)

N = total number of input flows

M = total number of output flows

XH, XL and Xs are respectively the stock of primary resource, the stock of waste and the stock of final products just explained.

XT = total stock

The total amount of resources entering the system any time step must be equal to the total amount of resources exiting the system plus the variation in the stocks. For the balance there is no difference between final products and resources, what is important is that no mass or energy is generated or destroyed during the production process.

As convention, what is left from the recycling conversion efficiency γ (the amount of waste that is not recycled) goes back to the originating stock of waste XL . The model gives also the possibility to analyse energy exchange between farms. In that case, the energy flows move from the XH (or $XBio$) of one farm to the XH of another farm, so that they are accounted in equations 2.14 and 2.15 without changing the structure of the balance.

2.5 Multiproduct engine:

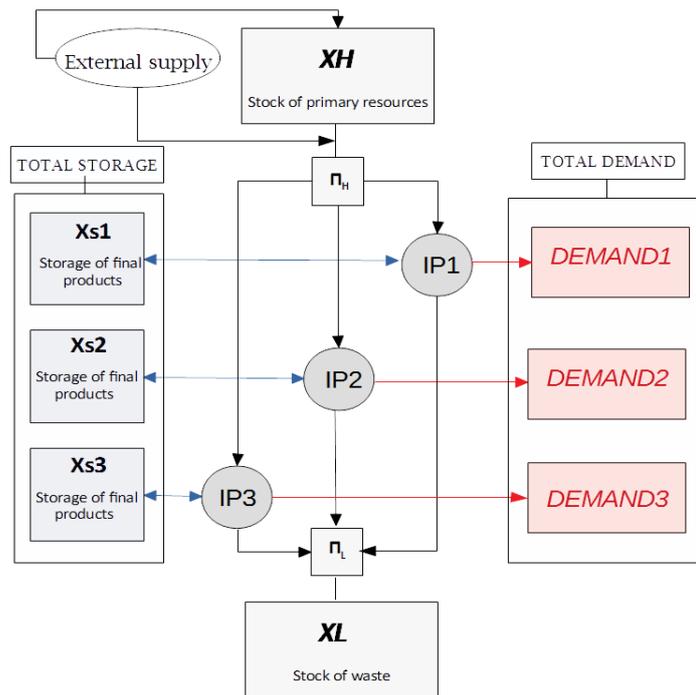


Figure 9 - The multiproduct engine

While for food engine is possible to assume only one product. In other words, from feed, animals generate only one useful product. It is not possible to say the same for energy. Inside the system, primary resource is converted in heating, ventilation, pumping, lightning and several other uses. In this case, the engine is developed as multiproduct engine where several productions are in competition for the same resource. Multiproduct engines work as single product engines but when the available resource is not sufficient to satisfy every demand, the multiproduct engine will satisfy demands, one per time, in the order of importance set by the user. The global demand will be the sum of all demands considered. The total

storage will be the sum of the single storage systems but any storage is treated independently.

2.6 Interconnection between farms

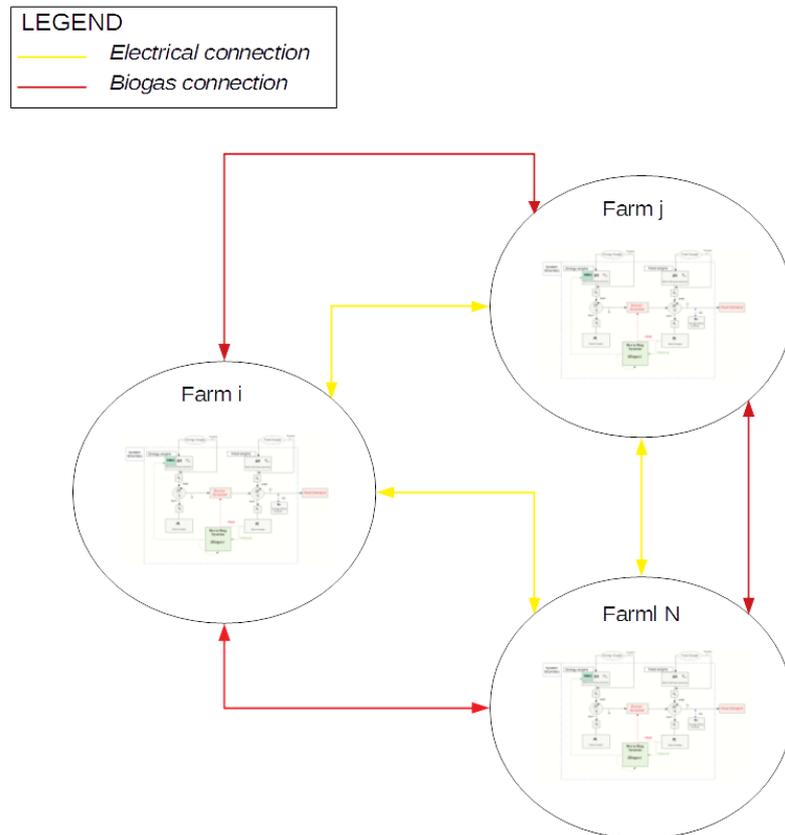


Figure 10 – Energetic interconnection

The adaptability of the system to intermittent sources of energy is strictly related to the available storage and the matching supply-demand any time step. All these points improve with an energetic interconnection between farms.

Figure 10 shows two different connections for electricity and biogas. As in reality, also the model make this distinction. The “stock and flow” logic used to model the single farm permit to interconnect easily several farms considering the exchange as flows of resources moving from one stock to another. Once interconnected, the priority pass from the single farm to the system. Meaning that the single farm could reduce its personal energy demand satisfaction to maximize that of the system.

Following the logic of [54], how to distribute energy among interconnected nodes depends on the priority of one upon the other.

Between farms there is no priority, they have equal rights in terms of energy. Always [54] suggest methods for a fair distribution of energy.

The logic used for energy exchange is “fair and proportional”, meaning that energy is distributed proportionally to the demand and there is no reason why one farm should receive while another should not if both require energy.

Microgrids and electricity exchange

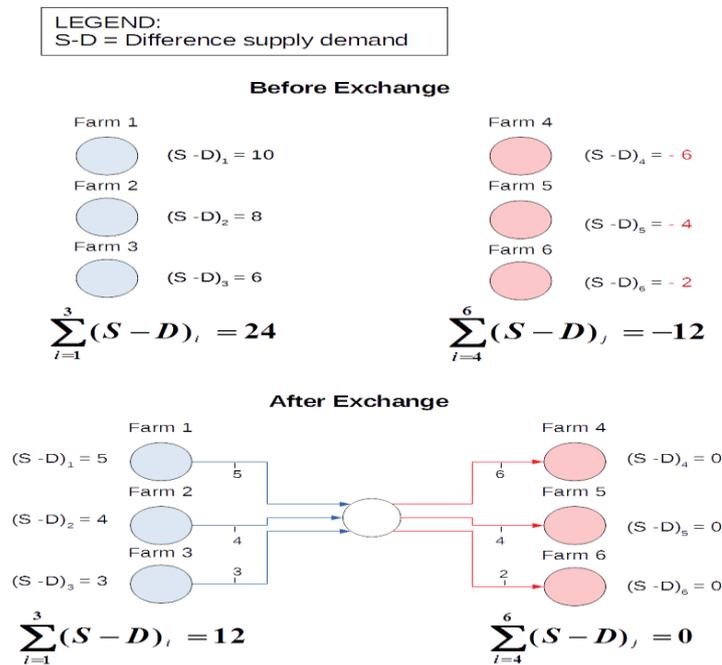


Figure 11–Instantaneous proportional exchange, algorithm working principle

Figure 11 shows the working principle of the “fair and proportional” exchange of energy for microgrids. The first three farms have an excess of supply of 24 units. For farms 4, 5 and 6 is the opposite, their demand exceed their supply for -12 units in total. The first three farms give energy proportionally, in fact *Farm 1* has 10 and gives 5, *Farm 2* has 8 and gives 4 and *Farm 3* has 6 and gives 3. If the sum (S-D) of farms 1, 2 and 3 was 6 instead of 24, they would give all the excess of production and farms 4, 5 and 6 would receive respectively 3, 2 and 1.

It is important to notice that the first three farms give just the energy necessary to bring all the other farms at (S-D) = 0. The rest 12 units could be stored or simply lost depending on the conditions. If there is energy stored, clearly also that energy

contributes to satisfy demands. Here, is described the logic of exchange only for satisfaction of the instantaneous demand.

The electrical interconnection adapt easily to the logic described in *Figure 11* for Biogas is necessary some additional consideration.

Bio-methane exchange

Raw biogas consists mainly of methane (CH₄, 40-75%) and carbon dioxide (CO₂, 15-60%). Trace amounts of other components such as water (H₂O, 5-10%), hydrogen sulphide (H₂S, 0.005-2%), ammonia (NH₃, <1%), oxygen (O₂, 0-1%), carbon monoxide (CO, <0.6%) and nitrogen (N₂, 0-2%) can be present and might be inconvenient when not removed.

Independently from the typology of exchange, biogas needs to be converted in bio-methane and depurated before to be exchanged.

Natural gas is generally transferred through pipelines but bio-methane must respect purity standard before to be introduced. There are prototype projects of suitable pipelines for bio-methane especially in the Scandinavian Peninsula. Another chance is to transfer large quantities of bio-methane with tracks in form of CBM (Compressed Bio-Methane) or LBM (Liquefied Bio-Methane). [55]

Due to the diversified nature of bio-methane exchange, the logic used is to equalize the stocks (XBio) at their average value for any exchange. This methodology permits to represent the exchange both through pipelines and through trucks and keep the logic of proportionality and equality. The lower is the stock to the average value the more it receives. The higher is the stock to the average value the more it gives.

The exchange is instantaneous, meaning that it happens within one time-step. This assumption adapt easily to pipelines case. Exchange through tracks can require more time-steps. The higher is the energy transported by trucks or the lower is the effective time necessary, the lower is the error derived by the approximation. [Appendix 4]

2.7 Modelling energy demand

The model differentiate closed and open spaces. Closed space, as the name suggest, represent sheds that are generally closed, where the recirculation of air is managed through mechanical ventilation. Open space represent sheds where natural ventilation plays an important role or completely devoid of walls.

Closed spaces

The evolution of inside conditions of a shed can be modelled, without appreciable errors, with four principal contributions: ventilation, heat released by animals, heat transfer through the walls of the shed and energy consumed to keep the energetic balance.

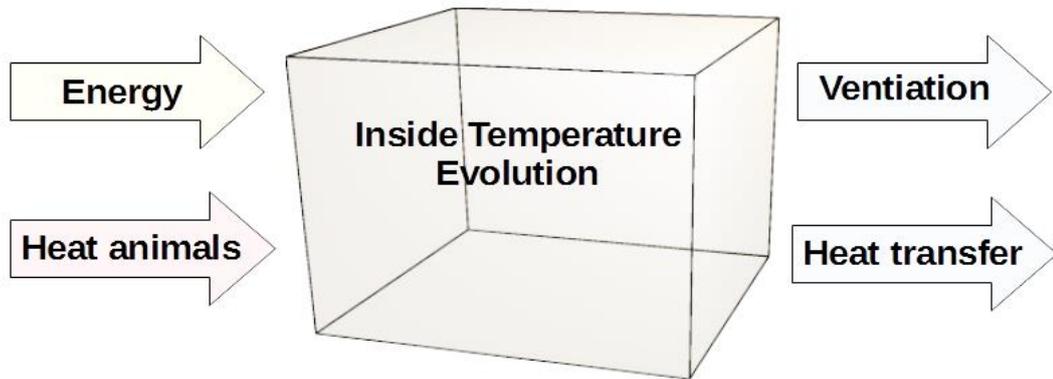


Figure 4 – Energy balance inside the farm

Making a simple balance:

$$\mathbf{Energy} = (\mathbf{Ventilation} + \mathbf{Heat\ transfer}) - \mathbf{Heat\ Animals} \quad (2.16)$$

If the sum *Ventilation* and *Heat transfer* is higher than *Heat Animals*, the *Energy* term will be positive (heating). Vice versa, it will be negative (cooling).

It is possible to evaluate any member, knowing that the inside temperature must be kept at “ T_{target} ” any time-step.

$$\mathbf{Ventilation} = \rho_{air} \times V_{air} \times cp_{air} \times (T_{target} - T_{ext}) \quad (2.17)$$

cp_{air} = heat transfer coefficient of the air [$\frac{\text{kJ}}{\text{kgK}}$]

V_{air} = volume of air [$\frac{\text{m}^3}{\text{h}}$]

T_{ext} = external temperature [°C]

$$\text{Heat transfer} = U \times S_{\text{tot}} \times (T_{\text{target}} - T_{\text{ext}}) \quad (2.18)$$

U = global heat transfer coefficient [$\frac{\text{W}}{\text{m}^2}$]

S_{tot} = total surface [m²]

$$\text{Heat Animals} = N_{\text{animal}} \times H \quad (2.19)$$

N_{animal} = total number of animals

H = heat released by one animal

$$\text{Internal energy variation} = m \times cp \times (T_{\text{target}} - T_{\text{in}}(t-1)) \quad (2.20)$$

m = total mass of the building [kg]

cp = heat transfer coefficient of the building [$\frac{\text{kJ}}{\text{kgK}}$]

Substituting equations (2.17), (2.18) and (2.19) in (2.16), accounting for (2.20) and expressing everything as function of time, the energy demand will be:

$$\begin{aligned} D_{\text{energy}}(t) = & (U \times S_{\text{tot}} + \rho_{\text{air}} \times V_{\text{air}} \times cp_{\text{air}}) \times (T_{\text{target}} - T_{\text{ext}}(t)) - \text{Heat Animals} + \\ & + m \times cp \times (T_{\text{target}} - T_{\text{in}}(t-1)) \end{aligned} \quad (2.21)$$

Thanks to equation (2.21), it is possible to estimate any time step the energy demand $D_{\text{energy}}(t)$.

If the interest focus exclusively in the accounting of the energy required to keep the balance any time step at T_{target} , the last member of equation 2.21 will be always zero. This calculation correspond to the amount of energy required by the farm to keep desired internal conditions if there is always available energy.

If the interest focus to understand the evolution of the inside conditions in absence of energy to keep the balance the evolution of the system can be studied considering that, if at time step "t" $Available\ Energy(t) < D_{energy}(t)$ then $T_{in}(t) \neq T_{target}$ and the last member of equation 2.21 will be higher than zero. $D_{energy}(t+1)$ will be higher than the ideal case.

From these considerations is possible to derive a more general expression.

$$P(t) = \text{energy produced}; P(t) \leq D_{energy}(t) \text{ always}$$

$$P(t) = (U \times Stot + \rho_{air} \times V_{air} \times cv_{air}) \times (T_{in}(t) - T_{ext}(t)) - \text{Heat Animals} + m \times cp \times (T_{in}(t) - T_{in}(t-1)) \quad (2.22)$$

If $P(t) < D_{energy}(t)$, $T_{in}(t) \neq T_{target}$, $D_{energy}(t + 1)$ increases

if $P(t) = D_{energy}(t)$, $T_{in}(t) = T_{target}$, $D_{energy}(t + 1)$ does not change

Open or semi-open spaces

In this case, differently from closed space, the internal temperature is supposed to be equal to the external one. $T_{in}(t) = T_{ext}(t)$ always.

This case is related to those animals, able to live without problems at very low external temperature. In this case, the energy balance is not present because there is not an internal temperature to keep. Since the space is considered open, animal's heat is directly released in the ambient. *The only issue is related to heat stress in summer, when the external temperature is generally higher than the acceptable one. Generally, a mix of water refreshing and ventilation is used to help the animals. The simplification assumption here is that, if the level required by literature are respected, the perceived temperature moves back to the acceptable range instantaneously.*

2.8 Criteria to size the renewable plant

2.8.1 Renewables

A compact and simple methodology to compare renewables and distributed energy with the external grid have been developed to simplify the comparison between several plant alternatives.

It is possible to imagine at the national grid as an ideal plant, perfectly dispatchable and sized to produce in the year exactly what is required. The limits of renewable production can be analysed trying to make the same assumption. If the renewable plant is sized to equalize annual production and annual demand, it likely will not satisfy demand any time step because production does not follow demand (not dispatchable source).

Three principal factors to size the plant: the coupling factor λ , the dimensioning factor \mathbf{B} and the over-dimensioning factor \mathbf{N} . [23], [25]

Considering a total number of renewable technologies T ($t_1, t_2 \dots t_T$) and a total number of energy loads D ($d_1, d_2 \dots d_D$):

$$\mathbf{E}_{\text{required}} = \sum_{d=1}^D \mathbf{e}_{\text{required-d}} \times \mathbf{S}_d \quad (2.23)$$

$$\mathbf{B}_t = \frac{\sum_{d=1}^D \mathbf{e}_{\text{required-d}}}{\mathbf{e}_{\text{produced-t}}} \quad (2.24)$$

$$\mathbf{S}_t = \mathbf{S}_D \times \mathbf{B}_t \quad (2.25)$$

$$\mathbf{E}_t = \mathbf{e}_{\text{produced-t}} \times \mathbf{S}_t \quad (2.26)$$

t = generic renewable technology

d = generic energy load

S = Surface [m^2]

$$E_{\text{required}} = \text{Total energy required} \left[\frac{\text{kWh}}{\text{y}} \right]$$

$$e_{\text{required-d}} = \text{Energy required per square meter of load d} \left[\frac{\text{kWh}}{\text{m}^2\text{y}} \right]$$

$$e_{\text{produced-t}} = \text{Energy produced per square meter of technology t} \left[\frac{\text{kWh}}{\text{m}^2\text{y}} \right]$$

$$E_t = \text{energy produced by technology-t to equalize } E_{\text{required}} \left[\frac{\text{kWh}}{\text{y}} \right]$$

B is the ratio between the yearly energy needs of 1 m^2 of energy demand, compared to the yearly production of 1 m^2 of the considered technology. Knowing the total surface of demand is possible to derive the plant size required.

$$\mathbf{E}_{\text{produced}} = \sum_{t=1}^T \lambda_t \times \mathbf{E}_t ; \sum_{t=1}^T \lambda_t = 1 \quad (2.27)$$

Once known the annual demand and the plant size of each technology required to equalize it, the coupling factor λ describes how the total is shared between the considered technologies. In other words, the energy mix that equalize annual production and annual demand.

$$\mathbf{E}_{\text{produced}} = \mathbf{N} \times \mathbf{E}_{\text{required}} \quad (2.28)$$

Finally, as described in (2.28) it is possible to choose to over-size or to under-size production thanks to the over-dimensioning factor N .

To resume, the procedure simply equalize annual energy production and demand but thanks to equations (2.24), (2.25) and (2.27) is possible to know the size of the plant and the energy mix required.

It is important to remark that all factors and coefficients described, permit to size the plant in order to have an equality between production and demand just in terms of total annual demand. This does not mean that any time step demand is

satisfied. For any time step, if $supply(t) \geq demand(t)$ demand will be satisfied, if $supply(t) < demand(t)$ demand will be not satisfied.

2.8.2 Biogas Production

Biogas production starts from manure generated by animals. As seen, the animal engines gives an estimation of the energy contained in the manure starting from the energy contained in animal's feed. In the biogas production process, only a certain percentage of this energy is convertible.

Literature generally express biogas production in terms of dry matter or percentage of volatile species contained in the manure [56] , [30]. In fact, this fraction is the only one that bacteria can digest to produce bio-methane.

The evaluation of the dry matter content is not univocal; it takes into account the animal's diet and the composition of the manure, here estimation is based on [28], [29].

On the base of these considerations, the following procedure is used to account biogas production:

$$MP = X \times AAW \quad (2.29)$$

$$DM = Y \times MP \quad (2.30)$$

$$BP = DM \times BY \times FBM \times LHV_{Bio-methane} \quad (2.31)$$

$$\gamma = \frac{BP}{ME} \quad (2.32)$$

MP = manure production $\left[\frac{kg}{day\ animal}\right]$

AAW = Average animal weight [kg live weight]

DM = Dry matter produced $\left[\frac{kgDM}{day\ animal}\right]$

X = percentage of AAW [%]

Y = percentage of MP [%]

BY = Biogas yield [$\frac{m^3}{kgDM}$]

LHV_{Bio-methane} = Lower Heating Value Bio-methane [$\frac{kWh}{m^3}$]

FBM = Fraction of bio-methane in the biogas [%]

BP = Bio-methane Production [$\frac{kWh}{day\ animal}$]

ME = Manure Energy [$\frac{kWh}{day\ animal}$], *energy contained in the animal's manure*

γ = recycling conversion efficiency [%]

“ γ ” is the coefficient that represent the fraction of energy contained in the manure available for bio-methane production. It is the revisiting of the typical approach used to estimate biogas extractable from animal's manure suitable for this model. It connects directly animals' manure production to energy production giving a more compact evaluation of the animal engine's biogas potential. BP is expressed in kWh of bio-methane; this choice is principally related to the eventual possibility of biogas exchange.

2.9 Economic analysis

The simulation model is able to generate all principal parameters necessary for an economic analysis (size of plant and storage system, size of biogas plant, advantages of energy exchange...etc.) but is not able to perform an economic analysis by itself. The economic analysis have been developed using Excel and is based on the logic of the Levelised Cost of Energy (LCOE) and the Net Present Cost (NPC) used in “HOMER Energy - Hybrid Renewable and Distributed Generation System” a hybrid power system optimization software [5].

Net Present Value (NPV) and Levelised Cost of Energy (LCOE)

By definition Levelised cost of energy is a stream of equal payments, normalized over expected energy production, which would allow a project owner to recover all costs, including financing and an assumed return on investment, over a predetermined financial life.

$$\mathbf{LCOE} = \frac{\mathbf{I}_0 + \sum_{t=1}^N \frac{\mathbf{C}_t}{(\mathbf{1} + \mathbf{r})^t}}{\sum_{t=1}^N \frac{\mathbf{E}_t}{(\mathbf{1} + \mathbf{r})^t}} \quad (2.33)$$

The net present cost (or life-cycle cost) of a component is the present value of all the costs of installing and operating the component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime.

$$\mathbf{NPV} = \sum_{t=0}^N \frac{(\mathbf{Benefits}_t - \mathbf{Costs}_t)}{(\mathbf{1} + \mathbf{r})^t} - \mathbf{I}_0 \quad (2.34)$$

$$\mathbf{NPC} = - \mathbf{NPV} \quad (2.35)$$

NPV = Net Present Value [€]

LCOE = Levelised Cost of Electricity [€]

i or t = year

N = total number of years considered (life-time)

Benefits = Benefits derived from the investment $\left[\frac{\text{€}}{\text{y}} \right]$

E = Energy generated or energy stored $\left[\frac{\text{kWh}}{\text{y}} \right]$

I₀ = Initial investment cost [€]

Costs = Costs derived from the investment $\left[\frac{\text{€}}{\text{y}} \right]$

r = discount rate

The LCOE explain what should be the revenue of any single kWh produced by the considered power plant in order to recover all costs within its lifetime. It is used to compare different plant alternatives and choose the most affordable solution for an energy investment. Anyway, in this study, any energy producer is at the same

time consumer and before to sell energy to the grid it tries to consume it. Moreover, the eventual introduction of biogas in the energy mix generates additional considerations. Biogas can be converted in different energy forms that have different economic values and can be exchanged, generating additional costs and benefits. In these terms, the LCOE cannot suitably describe the dynamics of the investment and could generate excessive approximations or incorrect evaluations. LCOE is a tool effective principally for power plant producer that aims to sell their energy to the national grid. For this reason, it has been supported by the NPV-NPC that, having benefits contained in its formula, better describes the evolution of the investment and permits to compare more accurately different alternatives.

If the cash flow in the year is already sufficient to describe the investment, then a simple cost-benefit analysis in the year will be preferred to the actualized cost represented by the NPV.

3 Case study

This chapter aims to describe how model inputs and system parameters have been calibrated. The sources, the principal assumptions and the simplifications used to describe reality. The subject of study and the study targets.

- **Where:** Île-de-France, France.
- **When :** 2018 (from 2018 to 2043 for investments analysis)
- **Who:** Subject of study is the French agro-productive system. In particular, the attention focus on livestock. Animals considered are poultry, pig, cattle and goat. It is analysed production of poultry's eggs and meat, pig meat, cattle's milk and goat's milk.
- **Targets:** To analyse and quantify the possibility of the French Livestock to become 100% energetically self-sufficient using renewable energy. To simulate the impact of partial energy demand satisfaction on animal's production. To evaluate the economic affordability of the energy shift.
- **Used to achieve targets:** Wind turbines, photovoltaic panels, biogas-anaerobic digester, Li-Ion and Lead Acid battery, PEMFC storage system, Compressed Air Energy Storage (CAES), Microgrids and bio-methane exchange for energy self-sufficiency. Animals and farms characteristics for demand satisfaction impact. Incentives and subsidies for economic affordability.

Next chapters will describe in detail what resumed here. In particular, chapter 3.2 describes animals and farms characteristics, chapter 3.3 focus on power plant and storage system, finally chapter 3.4 describes incentives, subsidies and principal costs related to energy consumption.

3.1 Simulation data

All climate data and data related to photovoltaic and wind turbines production come from the database and related works of the LIED-PIERI (Laboratoire Interdisciplinaire des Energies de Demain- Paris 7 Interdisciplinary Energy Research Institute) laboratory associated to the university Paris Diderot where part of this thesis have been developed.

Script programming language: Python 2.7.1

Data:

- 7 hourly climate data (years 2006 – 2012).
- 7 hourly wind turbines and PV panels production data (years 2006 – 2012).
- 4 different animals: poultry, pig, cattle and goat.
- 28 prototype simulated farms to derive average values and interconnection effects.

Time:

- 1 year
- Hour as time-step used
- Any simulation moves from 1st April to 31st March.
- Seasonality in order: Spring, Summer, Autumn and Winter

Any simulation considers that the renewable plant starts to run at time step 1 and no energy is stored before to start operation.

Simplifications and assumptions: Climate and production data refers to the region Île-de-France, region of the capital Paris. The great part of breeding information refers to the region around Île-de-France: Normandie, Pays de la Loire and Bretagne in particular. Values found are considered as mean for all regions.

To estimate the effects of energy interconnection between farms it is necessary to have climate data of different geographic position (heterogeneity of renewable production and demand). Even considering the same region or the same province, small distances could imply weather variations. In order to do that with the available database, any year of the climate data have been considered as fictitious climate zone.

3.2 Livestock

The accounting of livestock's resources consumption, energy in particular, is a complex model, which takes into account the interaction of living being with the external environment. There are several variables influencing the system.

Table 4 lists the animals, the stages of life and the principal parameters considered.

	<i>Age</i>	<i>AAW</i>	ρ	T_{min}	T_{max}	N_a	T_{target}
Pig	Lactating pig	4	3.33	29	31	250	30
	Nursery pig	10	2.5	29	31	250	30
	Growing pig	60	1.25	15	25	250	18
Cattle	Dairy Cattle	500	0.14	-5	25	120	≤ 25
Poultry	Chicks	0.2	30	30	32	6000	31
	Chickens	1	15	24	26	6000	25
Goat	Adult Goat	70	0.5	-5	25	240	≤ 25

Table 4 - Livestock principal parameters

AAW = Average Animal Weight [kg]

ρ = Animal load [$\frac{\text{animals}}{\text{m}^2}$]

T_{min} = Minimum acceptable temperature [°C]

T_{max} = Maximum acceptable temperature [°C]

N_a = number of animals per farm

T_{target} = Target temperature considered for the energy balance [°C]

The total surface occupied by the farm can be derived multiplying the number of animals (N_a) and the animal load (ρ). T_{min} and T_{max} are the limit temperatures within which animals produce at maximum efficiency. Temperature and the other parameters derives by [57], [58], [19], [21]. The last three refers to highly detailed web site for animal's breeding.

Animal engine calibration

Literature proposes several relations between temperature and efficiency. In this case, any animal lose 4% of efficiency for any degree the internal temperature is out of desired values. This value have been estimated looking at results of [59], [60], [61] for different animals, anyway the evaluation of performance variation with temperature implies several variables and is not always linear. An average between results found is used to find a reasonable indicative value.

	<i>AAW*</i>	<i>DMF</i>	<i>FCF</i>	<i>FIE</i>	η	<i>FE</i>	<i>MF</i>	<i>ME</i>	<i>HF</i>	<i>H</i>
<i>poultry</i>	1.2*	8%	4.64	0.445	22%	0.1	50%	0.17	50%	0.17
<i>pig</i>	74*	4%	4.64	13.73	18%	2.47	50%	5.63	50%	5.63
<i>cattle</i>	500	3%	4.64	69.6	18%	12.5	50%	28.5	50%	28.5
<i>goat</i>	70	4%	4.64	13	18%	2.34	50%	5.32	50%	5.32

Table 5 – animal engine calibration

**For pigs and poultry, the AAW is the sum of the AAWs of all the ages considered*

Table 5 describes how the animal engine has been calibrated in this case study (see chapter 2.2 for animal engine). Values regarding DMF, FCF and efficiencies can be found in [62], [63], [19], [16]. From [16] it is extrapolated also the idea to consider animals as engine and the value of the efficiency (η) for any animal. What is left of the efficiency is shared 50% heat and 50 % manure [64].

Food Energy (FE) can be reconverted in kg of food. Indicatively 3227 kcal/kg meat, 1660 kcal/kg eggs and 707 kcal/kg milk [16].

Cattle produce manure energy in quantities substantially higher than the other animals even with the lower DMF because body weight is largely higher. Opposite reasoning is valid for chickens. Anyway, the number of chickens per exploitation is one or two order of magnitude higher respect to cattle and this can balance total production.

Poultry: The interest focus on both intensive production of meat and eggs, produced with same efficiency. Animals live in closed spaces where the inside temperature is kept at desired levels for their well living. Demand for chicks (first three weeks of life) and chickens (from 4th to 7th week of life) has same characteristics, it is principally characterized by heating and ventilation. [15],[58]

Pig: The interest focus on the production of meat. They live in a closed space where the inside temperature is kept at desired levels for their well living. Lactating pig (1st month of life) use infrared heaters instead of ambient heating systems and their demand is almost exclusively heating. Sows live with their babies in this first month. They accept temperatures around 21°C respect to the 30°C required by babies, then infrared heaters are used to heat up just lactating pigs, without increasing ambient temperature. Calculation of infrared consumption follow [65]. Nursery pigs require less heating, do not live with sows and do not use infrared heaters. Ventilation requirement increases. Growing pigs consume almost exclusively for ventilation. Once adult pig are able to accept lower temperatures and their bodies produce large quantities of heat. Heating needs become negligible while ventilation increases to avoid excessive temperature inside farms. For more details in [18],[19].

Cattle: The interest focus on milk production Demand for energy is analysed for adult animals. They live in an open or semi open space where the inside temperature is approximated to the external one. Demand is principally related to milk production and extraction. [20]

Goat: The interest focus on milk production. Demand for energy is analysed for adult animals. They live in an open or semi open space where the inside temperature is approximated to the external one. Demand is principally related to milk production and extraction. [22]

Different approaches derive from the biological thermoregulation capacity of the animal. Goats and cattle can live, without appreciable variation on their efficiency, in a range of temperature from -5°C to 25°C and even higher. On the other hand, poultry and pig have lower ranges of acceptability, especially in the first stages of their life. [57]

	<i>Poultry</i>	<i>Pig</i>	<i>Cattle</i>	<i>Goat</i>	<i>Average Conversion Factor</i>	<i>Unit of measurement</i>
<i>Heating</i>	✓	✓	✗	✗	1	kWh/kWh
<i>Ventilation</i>	✓	✓	✓	✓	7.5×10^{-5}	kWh/m ³ /h
<i>Water Pumping</i>	✓	✓	✓	✓	0.3	kWh/m ³ /h
<i>Nebulizator</i>	✓	✓	✓	✓	0.375	kWh/l/min
<i>Lightning</i>	✓	✓	✓	✓	1.6×10^{-5}	kWh/lumen
<i>Infrared Heaters</i>	✗	✓	✗	✗	1	kWh/kWh
<i>Milk pumping</i>	✗	✗	✓	✓	0.015	kWh/l _{milk}
<i>Refrigeration</i>	✗	✗	✓	✓	0.02	kWh/l _{milk}
<i>Water heating</i>	✗	✗	✓	✓	0.03	kWh/l _{milk}
<i>Share of total energy demand found in literature</i>	89%	97%	54%	34%		

Table 6 - List of energetic uses and share of total energy requirement

For all the animals is considered only a certain fraction of the total energy requirement found in literature. This fraction is related principally to the internal energy uses of the farms, excluding all indirect energy requirements. In particular, no energy uses related to vehicles for feed and animals transportation are considered. For pigs and poultry, the fraction is higher because the share refers to the internal energy requirements. For cattle and goat, literature demand takes into account also transportation of feed and animals that, as explained, is not taken into account in this study. Water heating refers to the water used to wash the milk tank. As assumption, no farm use automated systems for food distribution. Water pumping, ventilation and lightning is considered in all type of livestock.

Heating represent electric resistance heating, infrared heaters or boilers feed with methane. Conversion is considered unitary for these technologies since for methane conversion efficiency is accounted before to be introduced in the boiler, while electric heaters can be considered unitary efficient. Ventilation, nebulizators and water pumping average conversion factor is simply derived using an average value of the models described in catalogues (once known the cubic meter required) for this kind of applications. For ventilation, FC 050 4EQ.4F.3 and FC 056 4DQ.4I.V7 are chosen as reference. They require respectively 0.51 and 1 KW to move 8050

and 12300 m³/h. An average of 0.75 kW are used to move an average of 10000 m³/h

For water pumping, the reference model is “Lowara 2GS05” an immersion pump typically used in agricultural applications, it moves between 0-3 m³/h, with hydraulic height 30-70 m (metres of water column). As assumption, this pump is supposed suitable for all applications. The pump consumes 0.55 kW for applications that range around 1.5 m³/h then an average of 0.3 kWh/m³/h is estimated. Nebulizers use as reference IDROMIG catalogue using MIG PREMIUM pump for industrial applications that consume 1.25 kW to move 3-4 l/min.

Levels of ventilation and water pumping required for any season are extrapolated from [19], [21], [58].

Infrared heaters consumption have been derived equalizing heat production with the heat required by lactating pigs, computed using [65]. Lightning conversion consider typical technologies used for farms applications. Values required derive from French normative for lightning in agricultural applications. Milk pumping, refrigeration and water heating are directly extrapolated from literature [20].

Additional Parameters: Height buildings = 3 m, U = global heat transfer coefficient buildings = $0.75 \frac{W}{m^2}$ [15], C = Heat capacity building = 0.3 kWh/K (it consider just the air inside the building), $c_{p_{air}} = 1.005 \text{ kJ/kgK}$, $\rho_{air} = 1.225 \text{ kg/m}^3$

3.3 Renewable technologies and storage systems

Renewables technologies considered are:

- Photovoltaic panels (annual production 128 kWh/m²) [25]
- Wind turbines (annual production 160 kWh/m²) [2 3]
- Biogas digesters (%self-consumption, 22%) [33]

Storage systems considered are:

- PEMFC storage system (round trip efficiency = 31.5%) [35]
- Lead Acid batteries (round trip efficiency = 82%) [34]
- Li-Ion batteries (round trip efficiency = 95%) [34]
- CAES (round trip efficiency = 65%) [34]

	<i>Investment cost [€/kW]</i>	<i>Investment cost [€/kWh]</i>	<i>O&M cost [[€/kW/y]</i>	<i>Estimated Lifetime [Years]</i>
<i>Wind turbines</i>	1525	-	50	25
<i>Photovoltaic</i>	1730	-	24	25
<i>Biogas</i>	4000	-	160	25
<i>PEMFC storage* system</i>	3820	10	30	10**
<i>CAES*</i>	1950	10-40	95	25
<i>Lead Acid battery</i>	-	120	10	10
<i>Li-Ion battery</i>	-	610	10	16

Table 7 – Power plant and storage system costs

* Investment cost per kWh for CAES and PEMFC is exclusively the cost of the tank. The total investment cost is the sum of the two investment costs of Table 7

**10 years refers to the lifetime of the PEMFC stack. Lifetime for PEM electrolyser and hydrogen tank are respectively 15 and 25 years

Cost referred to wind turbines, PV panels and bio digesters have been calibrated using [40], [41], [42],[43]. Costs referred to storage systems have been calibrated using [35], [34], [44],[45] for batteries and fuel cells while [46],[47],[34] for CAES systems.

Investment costs refer to total installed costs and take into account all additional tools required (as inverters) for any technology. Lifetime for wind turbines, photovoltaic and anaerobic digesters range between 20 and 30 years depending on the manufacturer, here have been set 25 years for each technology since it is also the project lifetime. CAES systems have generally life expectancy higher than 25 years. Batteries lifespan have been estimated using [34] and are average values of the different technologies presented. Hydrogen fuel cell stack and electrolyser lifespan is estimated using [35] while the tank can range between 20 and 30 years depending on the typology used (25 years as average). More information in next chapters).

Other assumptions: No reduction of efficiency along the lifespan of any technology is considered. Distribution losses are considered negligible in the stand-alone case while equal to 6.5% of plant production in the Microgrid case[27].Reference costs are the same in the stand alone case and microgrid case.

3.3.1 Power Plant

All technologies considered have been modelled using a semi-realistic approach. They describe the potential energy achievable on the base of the wind velocity, solar radiation, manure characteristics and external temperature.

Wind turbines + PV panels

Wind turbines and photovoltaic panels have been chosen because consolidated renewable technologies, which have already penetrated the market and can be considered the most competitive respect to fossil fuels and nuclear.

Photovoltaic panels and wind turbines production data derives from two stage works of the LIED (*Laboratoire Interdisciplinaire des Energies de Demain*) associated to the University Paris Diderot where part of this study have been developed. Reference are [23],[25].

Horizontal axis wind turbines production data derive form the work of Marie-Cécile Dupas [23]. The modelling is based on a semi-realistic she derived power production using theoretical efficiencies with reference [24] at 80m height as reference. Cut in velocity 2 m/s. In order to give a reference power to this ideal

technology it is considered that for 3900 working hours, the velocity of the wind (at 80 m height) is indicatively between 5-9 m/s for 1700 hours, higher than 9 for only 150 hours and lower than 5 for 2050 h. As simple estimation, with this data, the reference velocity to choose an eventual nominal power is around 7 m/s that corresponds to indicatively 130 W/m² of nominal power. Estimated annual production 1075 kWh/kW.

[Velocity data is given at 10 m height. [23] compute production at 80m and the proportion used is $v_{80} = v_{10} * (\log(80/z_0) / \log(10/z_0))$ where v is the velocity at 80 and 10 m while z_0 is the "longueuer de rugosité"]. (see Appendix 1)

For photovoltaic panels production [25] reference is BP 585F mono-Si and the evolution of the efficiency is estimated using the equations suggested in [26]. Peak production is 135 W/m². Annual production 1145 kWh/kW.

For stand-alone applications, power distribution losses of both technologies are considered negligible.

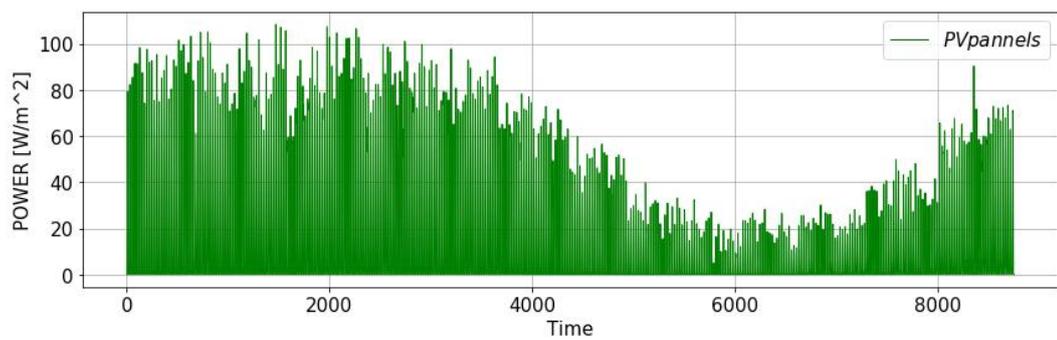


Figure 12- Average Photovoltaic panels production in the year

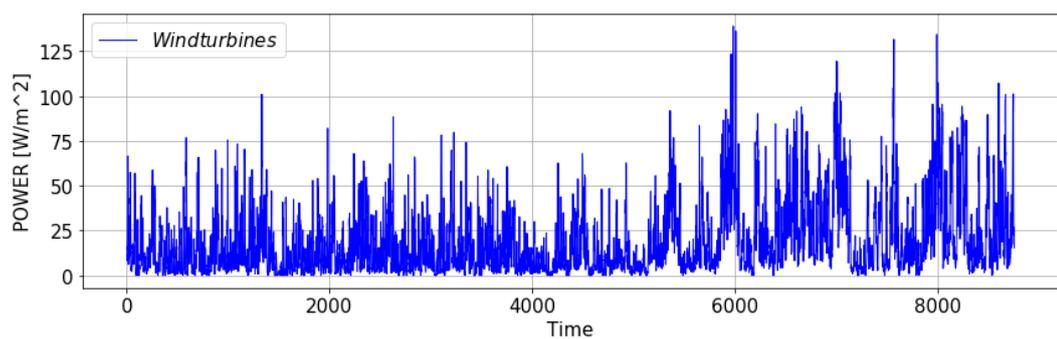


Figure 13- Average Wind turbines production in the year

Note: Any square meter of wind turbines refers to the area described by rotor of the wind turbine (vertical area) in order to know the ground area occupied (horizontal area) any squared meter must be multiplied by 35 [23].

In terms of power production, both technologies are strictly related to climate conditions and suffer of discontinuous and non-dispatchable generation. On one hand, wind turbines production is more homogeneously distributed in the year while PV panels have large discrepancy between summer and winter. Photovoltaic yearly production per square meter is higher 128 kWh/m² respect to 160 kWh/m² wind turbines.

To compare total installed cost of wind turbines and PV panels is not simple. They have similar range of costs and the relative advantage of one technology respect to the other depends on the site of installation and the size of the plant. In small-scale applications, PV panels are considered more competitive but increasing the size of the plant wind turbines becomes cheaper. In this study, the plant size moves from 30-200 kW for stand-alone applications to some MW in microgrid application. The reference plant can be considered in the order of 1-2 MW, in that case, wind turbines are a little bit more competitive[42]. In terms of O&M costs wind turbines results more expensive at parity of kW considered independently from the scale. The maintenance of solar arrays is relatively easy respect to wind turbines that are characterized by several mechanical organs. [40], [41].

Biogas

Biogas production can be considered the great energy potential of the agro-productive system since it is directly derived by its waste (more information in chapters 2.8.2.). The percentage of self-consumption is derived from literature [33], it takes into account electrical and heating needs of the bio- digester and is added the eventual compression of biogas to store it.

	AAW	X	Y	BY	FBM	LHV _{Bio-methane}	BP	γ
poultry	1.2	8%	25%	0.4	60%	10	0.057	0.33
pig	74	8%	10%	0.37	60%	10	1.31	0.23
cattle	500	8%	10%	0.24	60%	10	5.77	0.2
goat	70	4%	25%	0.27	60%	10	1.13	0.21

Table 8 - useful parameters to estimate animals' biogas production

All parameters here described refer to chapter 2.8.2 equations. Literature used to calibrate them is [28], [29] for X and Y while [30] for BY. FBM is supposed 60% for all animals and the LHV is the reference value of the Bio-methane's LHV in kWh/Nm³. To exploit all the energy contained in the animal's manure it is necessary that the organic loading rate (OLD) expressed in kg_{VS}/day is equal to the total amount of dry matter produced. For cattle and pig, this value correspond to 118 and 385 kg_{VS}/day. Ahlberg-Eliasson et al. [31] studied a total of 27 Swedish Farm scale biogas plant. They are used as reference to understand if the size of these plants is in the correct range. As average, plants based on cattle manure have OLR equal to 1173 kg_{VS}/day while pigs 1312 kg_{VS}/day. The annual biogas production of pig is between 130000-170000 m³/y while cattle between 55000-27000 m³/y depending on the volume of the digester. Here production is 19900 m³/y for pig and 41610 m³/y for cattle. The proportion respect to the reference values is respected also in terms of biogas produced.

For goat and chickens is not possible to have a direct comparison so that they are assumed to behave as cattle and pig.

In order to analyse the coherence of biogas production estimated with the method proposed in this study, the reference used is the work conducted by Kafle and Chen [32] for the journal "Waste Management". They used different statistical models to predict the biochemical methane potential of different livestock manures.

The literature results are, respectively for poultry, pig cattle and goat, 0.3, 0.429, 0.18 and 0.19 m³/kg_{DM}. Model results are respectively 0.395, 0.37, 0.24 and 0.27 m³/kg_{DM}.

Costs of the biogas plant installation derive from [42] while [66] is the reference for O&M costs.

Biogas respect to wind turbines and PV panels has the advantage to be dispatchable (unless there are problems to manage animals' manure to continuously feed the digester). Its production is more than the double of the other two technologies considered (2620 kWh_{eI}/kW·y) and does not depend on climate conditions (wind velocity, solar radiation...).

3.3.2 Storage system

In this case study, the role of the storage system is to store all the excess energy produced in the year by off-grid systems that aims to be energetically self-sufficient. For this reason, the Level of peak storage required could become high and expensive. In order to understand the affordability of storage system, it is interesting to compare different technologies with different characteristics.

Batteries: Li-Ion and Lead Acid

Li-Ion is the most efficient technology available in the market. Investment costs are higher respect to other technologies but the lifespan and the efficiency are higher. Lead Acid is less efficient than Li-Ion and its lifespan is lower but at the same time is cheaper. Following IRENA market forecasts, all batteries are expected to double their lifespan, to increase efficiency and to appreciably reduce their costs in the next 15 years [34]. Costs for batteries have been checked in [34] and [35]. O&M costs derive from [45].

In order to know the cost battery storage, the principal variable to take into account is the cost per kWh. The size in kW is important to ensure that batteries are able to absorb all the energy generated by the renewable plant: Performing batteries are the one with high power density (li-Ion) and are able to charge/discharge rapidly. Less performing batteries have lower power density (Lead Acid) and charge/discharge more slowly. Any technology have a range of Energy to Power ratio (kWh/kW) available[34], and clearly more performing batteries are more expensive, but all the models are in the same order of magnitude.

PEMFC Storage system

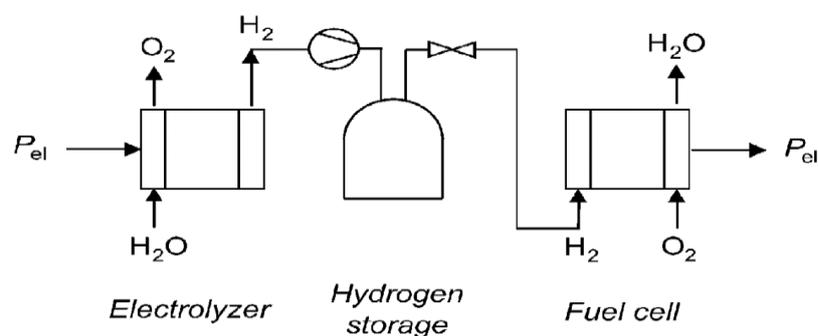


Figure 14 – Hydrogen storage system, schematic representation

Three principal components that structure hydrogen storage systems are: The electrolyser, which use electric power to separate hydrogen from water. The hydrogen tank, where hydrogen is stored at high pressures. The fuel cell stack, which use hydrogen to produce electricity, releasing water. The round trip efficiency (35% as reference [35]) takes into account losses in the electrolyser, tank and fuel cell. Moreover 10% of the energy contained in the hydrogen is considered internally used to compress it at high pressure [36]. The resultant efficiency is 31.5%. All these considerations bring the system to very low efficiency.

Compared to batteries cost, the cost of the tank can be up to two order of magnitude lower. The range of cost of tank is derived by [11],[34]. The great part of costs is contained in the PEMFC and the electrolyser. [35]

Fuel cells are technologies that have still not penetrated the market. There are projects and good expectations for their application in the automotive sector in the next years but reduction of costs for storage systems is still characterized by large uncertainty [67].

CAES

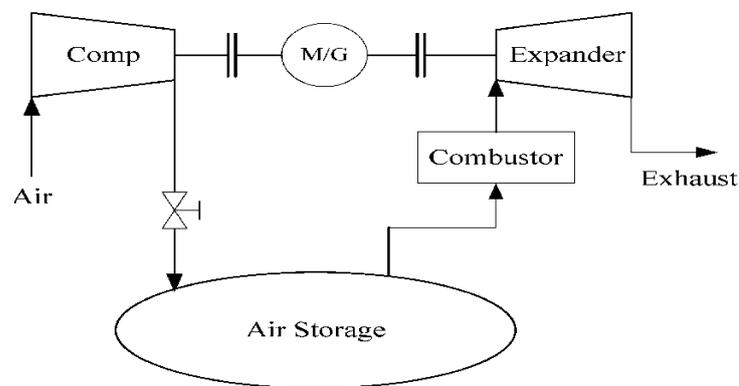


Figure 15 – CAES system, schematic representation

The working principle of CAES starts from the electric motor/generator (M/G). Using electricity coming from renewables the motor run the compressor to inject air in the storage tank at relatively high pressure. When electricity is required, the pressurized air is heated up and expanded in the expansion turbine that drives the generator for power production.

Respect to PEMFC, CAES is able to achieve higher round trip efficiency. Site geology influence storage price. Cost for gas storing varies with the presence of available geologic site and the eventual presence of caverns. In absence of caverns, more expensive metal tanks are used. Hydrogen is generally stored at very high pressure that largely reduce the volume of tank required and for small-scale applications the geologic site is not so relevant. Cost per kW is lower for CAES [47],[46] since turbines and compressors are technologies more consolidated respect to fuel cells. Anyway, O&M costs are largely higher due to the presence of the combustor and a more complex system[46]. A key challenge remains the lack of projects under development, and the outlook for CAES is highly uncertain.

3.3.3 Energy to Power ratio

The energy to power ratio (E/P) achievable by these two technologies is largely higher if compared to batteries. Compressing gas at high pressures permits to store large quantities of energy in a very small volume. If the mass flow rate required is low then is possible to achieve very large compression ratio (β) using few kW of compressor. Shakya, Aye and Musgrave [34] studied the technical feasibility of hybrid wind-photovoltaic systems with hydrogen storage. Plants analyzed are between 30 and 100 kW. A 3.7 kW compressor is sufficient to store hydrogen at 23 MPa of 5.5 m³ able to store 4995 kWh (considering hydrogen density of 30 kg/m³) and the power unit used is 6 kW. An interesting case study for CAES is presented by Jannelli, Minutillo et al. [37] that propose sizing methodology for small-scale CAES system. The power plant is composed of 33 kWp of PV panels; air is stored between 25 and 35 bar using a 3.7 kW compressor and the turbine used is a 1.35 kW, the tank is 40 m³. Wang ,Lu, MA et al.[38] give an estimation of 2-6 Wh/l for CAES system, the same range can be found in the IRENA documentation [34]. Using 4 Wh/l and 40 m³/kW as reference it is estimated an E/P of 160 kWh/kW.

	<i>Energy to Power Ratio</i> <i>[kWh/kW]</i>	<i>Ref</i>
<i>Li-Ion (max)</i>	0.5	[34]
<i>Lead Acid (max)</i>	10	[34]
<i>Hydrogen</i>	840	[39]
<i>CAES</i>	160	[37], [38]

Table 9 – Energy to power ratio for different technologies

Batteries are generally suitable for applications where is required a fast charge discharge of energy. They are compact, efficient, and does not present all the issues related to compression of gas at high pressure. For application that requires high E/P, where probably the charge/discharge time unit is days, weeks or months CAES and hydrogen are largely better.

3.4 Incentives and Subsidies

	Feed in tariff [€/kWh]	Subsidies [% investment]
Wind turbines	0.082	X
Photovoltaic	0.14	X
Biogas electricity	0.18	30%
Bio-methane	0.095	30%

Table 10 - French incentives available for renewables as feed in tariff or subsidies

Feed in tariffs are consultable on IEA (International energy agency) web site [68] or [43]. They refer to the actual incentives present in France for renewable production.

Key drivers are “Law No. 2000-108, dated 10 February 2000 (the Electricity Law)” and the “Grenelle 1-2 law” arisen after the environmental forum called the “Grenelle de l’Environnement”. More information about biogas incentives is in [43]. For wind turbines the feed- in tariff is ensured for the first 10 years, later on the value could varies between 0.028 and 0.082 €/kWh depending on the plant. Here is assumed that the maximum is kept along all the useful life of the turbines. Incentives for photovoltaic are higher and can touch 0.246 €/kWh. Tariffs are higher for building integrated facilities. Here the technology is supposed ground based, then the feed-in tariff moves around 0.14 €/kWh.

ADEME, French Environment and Energy Management Agency support investments in biogas production up to 30% of investment cost [69],[70].While for the other renewables no direct subsidies have been found.

Feed in tariffs are available only for electricity and methane injected in the national grid/pipeline. The benefit of internally consumed energy units is the avoided cost of energy, evaluated at national price.

3.5 National and energy exchange costs

	<i>Cost</i>	<i>Unit of measurement</i>
<i>electricity</i>	0.15	[€/kWh]
<i>Methane[CH4]</i>	0.07	[€/kWh]
<i>Truck cost</i>	2.6	[€/km]
<i>Labour cost</i>	1.4	[€/km]
<i>Fuel cost</i>	0.45	[€/km]
<i>upgrading</i>	6000	[€/m ³ /h]
<i>Access</i>	15000	[€/km]
<i>Microgrid</i>	6.5%	[% power plant cost]

Table 11 – Costs of national energy and energy exchange

“Agreste - Ministère de l'agriculture et de l'alimentation”, estimates 5000 agricultural exploitations in Île-de-France. The total surface of the region is 12000 km². Supposing a homogeneous distribution is possible to derive an average of 2.4 exploitations per km². The average distance between two farms can be considered the bisector of the square, equal to almost 1.4 km. The total distance travelled is the average distance between two farms multiplied by the number of farms. All data referred to biogas transport, upgrading and access to national pipelines derive from [71], [72].

Cost of electricity and methane in France follows information of Selectra web platform [73].

Due to the impossibility to find a reasonable estimation of microgrid costs and losses in literature, they are simply estimated as the cost of additional plant necessary to recover national transmission and distribution losses. Source for losses: www.worldbank.org “Electric power transmission and distribution losses (% of output), France [27].

4 Results

This chapter aims to show results derived by the application of the model to the case study. Will be presented first the evolution of energy demand in the year. Then will be explained how the plant have been sized to satisfy demand, the energy mix used, the influence of energy storage and energy exchange. Last pages focus on the effects of partial satisfaction of energy demand on farms production.

It is also remarked that all simulations move from 1st April to 31st March.

4.1 Presentation of plant alternatives

Differently from optimization models, which have as objective to find the best solution among several alternatives. Simulation models have as objective to replicate reality and to give information about consequences and effects of predetermined choices. In these terms, it is important to clarify what are the alternative solutions that must be compared.

	<i>N</i>	<i>Biogas</i>	<i>Renewables</i>	<i>Microgrid</i>	<i>Biogas exchange</i>	<i>Electrical Storage</i>
<i>Chapter 4.3</i>	1	0	100%	X	X	X
<i>Chapter 4.4</i>	1	0	100%	X	X	✓
<i>Chapter 4.5</i>	1	69%	31%	X	X	X
<i>Chapter 4.6</i>	1	69%	31%	✓	X	X
<i>Chapter 4.7</i>	1 Cattle =1.25	69%	31%	✓	✓	X

Table 12 - Presentation of renewable plant alternatives described in results.

The assumption is to keep always N equal to one (see chapter 2.8). Anyway in the last case, since cattle achieve N = 1.25 with biogas, it is analysed the exploitation of all biogas available. The basic case consider only wind turbines and PV panels (Renewables) without storage system integrated. Then it is analysed the

introduction of different storage alternatives. In the third case, biogas enters in the energy mix. Last two cases consider the introduction of microgrids and bio-methane exchange.

4.2 Energy Demand

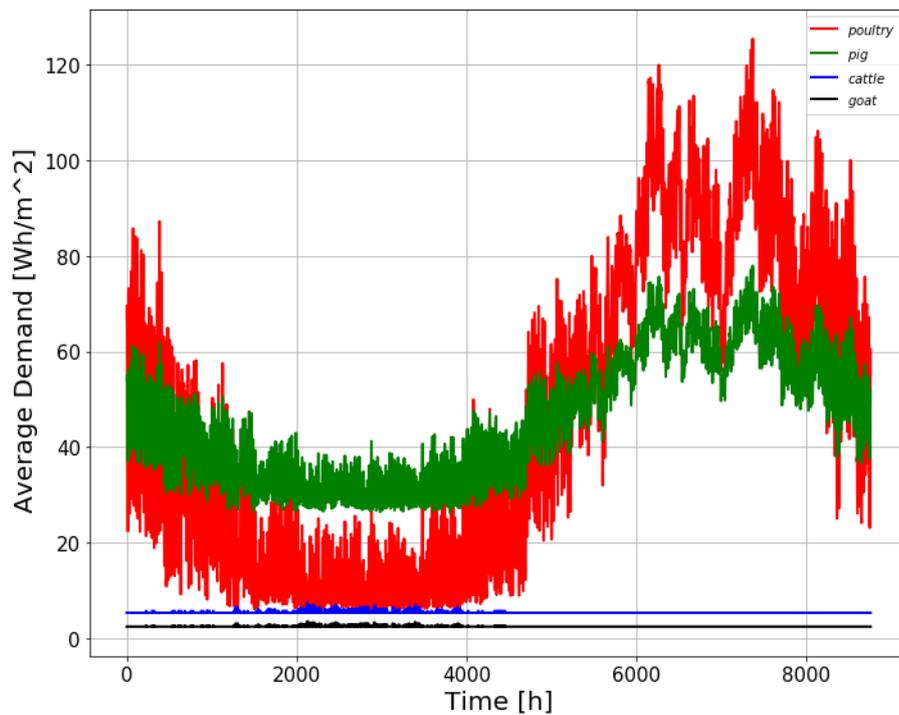


Figure 16 – Energy demand evolution in the year for any animal considered

Peak demand poultry 125 W/ m² average demand 46 W/ m² , peak demand pig 78 W/ m² average demand 45.5 W/ m² peak demand cattle 10 W/ m² average demand 6.4 W/ m² , peak demand goat 8.3 W/ m² average demand 5.2 W/ m².

Energy demand is presented in W/ m² because to size the plant, it is important to know how much energy requires in the year any farm’s square meter (see chapter 2.8).

Poultry curve has a higher variation during the year because its demand is principally characterized by heating (*Table 13*). Heating share is lower for pig while summer ventilation requires much higher levels respect to poultry. For this reason, during summer, poultry demand reduces of one order of magnitude while pigs have lower variations.

	<i>Heating</i>	<i>Ventilation</i>	<i>Milk extraction/storage</i>	<i>Other electrical uses</i>
poultry	94%	4%	X	2%
pig	50%	46%	X	4%
cattle	X	1.5%	79.5%	19%
goat	X	1.5%	75%	23.5%

Table 13 – Share of the principle energy uses inside farms

Cattle and Goat do not need heating during the year and their demand is principally connected to milk extraction and storage. Their demand is considered constant except for summertime, where both animals start to suffer for heat stress. In that case, water pumping and ventilation are activated to support animals.

The internal energy requirement for poultry and pig is around one order of magnitude higher respect to cattle and goat. Such difference is again related to heating that is much more energy expensive respect to lightning and mechanical requirements.

Comparison of energy demand with literature

Since the model aims to simulate farming, it is of interest to ensure that model's result are at least in the same order of magnitude of the values present in literature.

- **Poultry** : The report of the “Chambre d’agriculture de la Bretagne et Pays de la Loire” [15] related to poultry breeding explain that between 80 and 100 W/m² of heating system is generally installed. Here the peak demand is 120 W/m². As average consumption, the value reported is 1.87 kWh/animal/year with an animal load of 30 chickens/m². In the model, the result is 4 kWh/animal/year but the animal load considered is 15 chickens/m². Then, considering for both an animal load of 30 chickens/m² the model result is 2 kWh/animal/year. The share is similar to the model (*Table 13*) 88.7% heating and 12.3% electrical uses at parity of demand considered.
- **Pigs** : the “ifip-institut du porc” report [18] does not give information in terms of square meter of farm. It gives a national average consumption of 0.5 kWh/kg/y. Here the result is 2 kWh/kg/y a little bit overestimated but considering that Ile de France is in the north of France (colder region), it becomes more reasonable. The share is similar to the model (*Table 13*) 46%

heating and 54% electrical uses, whose 40% is ventilation, at parity of demand considered.

- **Cattle and Goat:** Since their demand is directly extrapolated from literature, it is useless to compare them with literature.

Comparison of food production with literature

	<i>model</i>	<i>literature</i>	<i>ref</i>
<i>Poultry meat [g/day]</i>	26.6	40	[17]
<i>Poultry egg [g/day]</i>	51.2	60	[58]
<i>Pig meat [g/day]</i>	650	710	[19]
<i>Cattle milk [l/day]</i>	15.2	18	[21]
<i>Goat milk [l/day]</i>	2.85	2.5	[74]

Table 14 – Food production, comparison between model and literature

All productions seem to be coherent with the typical values that can be found in literature for the considered animals. These values can change on the base of the kind of breeding (intensive or biologic), the diet of the animals or the use of particular technics of breeding. What is important is that the model respects the correct range of production of any animal and does not give incoherent values.

4.3 Sizing the renewable plant

As introduced, plant sizing is based on sizing factor **B**, over-sizing factor **N**, coupling factor λ and the target 100% renewable production. Once known the annual production per square meter of each technology and the annual demand per square meter of any farm, B can be easily derived making the ratio between the two. Respectively for poultry, pig, cattle and goat **B_{photovoltaic}** is **3.28, 3.46, 0.45 and 0.38** while **B_{wind-turbines}** is **2.7, 2.83, 0.37 and 0.31**. N is equal to one always, because one represent the minimum plant size necessary to ideally satisfy energy demand in the year. Also considering a perfectly dispatchable plant, if N is lower than one is impossible to satisfy 100% of energy demand.

Figure 17 shows the levels of satisfaction of total energy demand using several λ . λ equal to zero represent the plant 100% wind turbines. λ equal to one represent the plant 100% photovoltaic. As expected, using more technologies is more reliable than using only one technology. All animals, except for goat that increase a little bit

more up to 40%, find their maximum at $\lambda = 35\%$. Also considering global satisfaction of the system (blue line), the maximum is in $\lambda = 35\%$, so that, this value have been chosen for plant sizing. In details, poultry achieve 30% pig 38.8%, cattle 40.6 %, goat 38.84% and the entire system 34.67% of satisfaction. As expected, sizing the plant to equalize total annual production and total annual demand is not sufficient to achieve 100% satisfaction target.

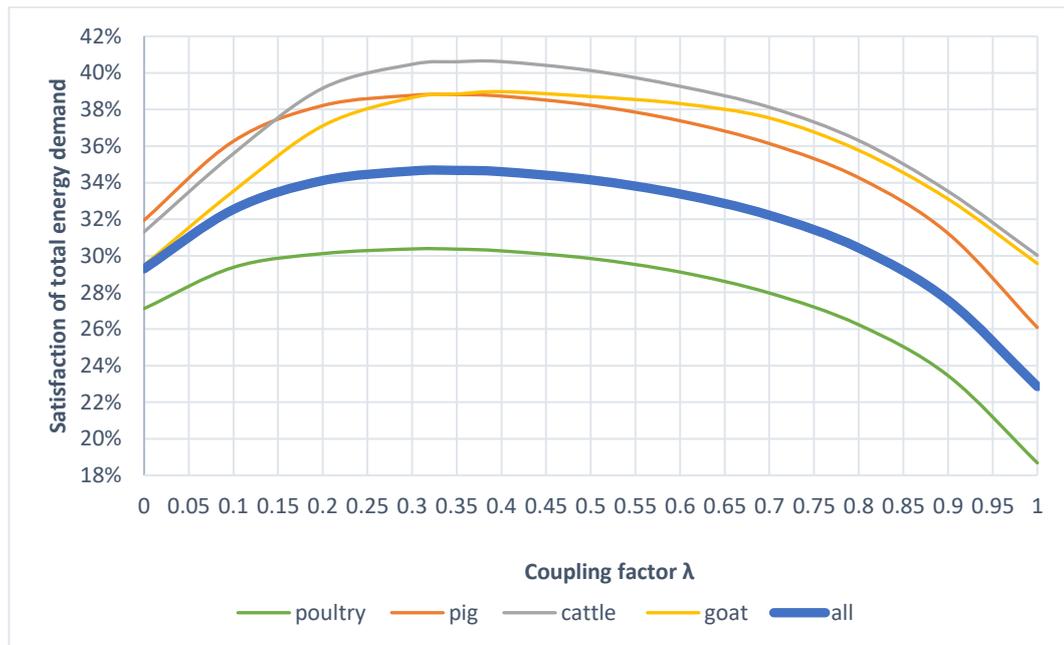


Figure 17 – Energy demand satisfaction using different values of λ

The sizing factor B shows how renewables respond to different energy demand. For poultry and pig that have higher demand, strongly characterized by heating, the sizing factor is around three. For cattle and goat that have lower energy demand, principally characterized by electrical uses, B is between 1/2 and 1/3.

In terms of power, around 370 Wp of photovoltaic or 380 Wp of wind turbines are necessary for any square meter of poultry and pig farms. For cattle and goat, the same power is sufficient for 9-11 m².

Photovoltaic needs to be a little less oversized respect to wind turbines to equalize annual demand but at parity of energy produced, 100% wind turbines achieve higher levels of satisfaction respect to 100% photovoltaic, especially four poultry and pig. This can be explained because photovoltaic panels in winter reduce drastically their production while wind turbines production is more homogenously distributed in the year (see Figure 12 and Figure 13).

At the actual state total energy demand satisfaction moves between 30% and 40%. There are four possible solutions to improve this condition:

- To increase the size of the power plant
- To introduce a storage system
- To introduce other renewable technologies able to increase the matching supply-demand during the year
- To enable farms to exchange energy and support each other

The first alternative is the simplest but the less efficient since implies additional oversizing of the renewable plant and difficulties to store energy.

Next chapters will try to quantify the effects of the following choices, to compare them and to understand their limits. The logic remains “ $N = 1$ ”, but what is expected to increase is the satisfaction during the year, the matching supply-demand any time step.

4.4 Introducing storage

Energy storage is almost indispensable using renewables. When production exceeds demand, energy can be stored and used in the opposite situation. If it was possible to perfectly store 100% of energy produced, it would be possible to achieve 100% self-sufficiency target.

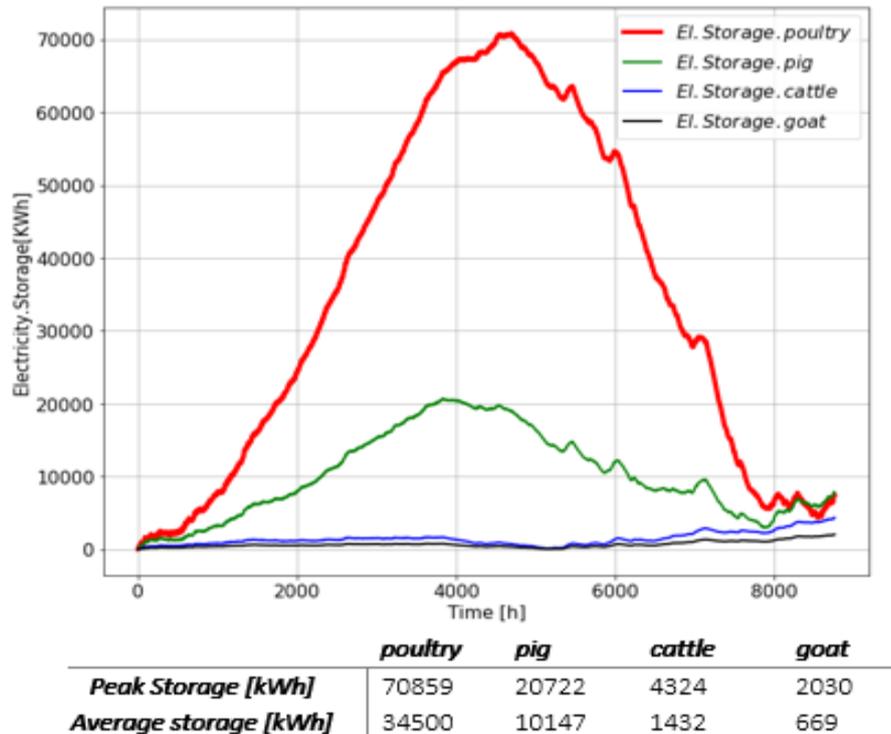


Figure 18 – Levels of energy storage required in the year

Storage system requirements become mirrors of energy demand. Poultry and pig have minimum demand during summer (*Figure 16*) while maximum in winter. For the power plant is the opposite (*Figure 12 and Figure 13*). Since yearly energy production and demand are equalized, during summer, the power plant produces great part of the energy necessary in winter. To store all this energy, the level of peak and average storage become extremely high. For cattle and goat, levels of storage are one or two order of magnitude lower. Their demand is lower and approximately constant in the year. Moreover, peak demand is in the same period of peak production (summertime).

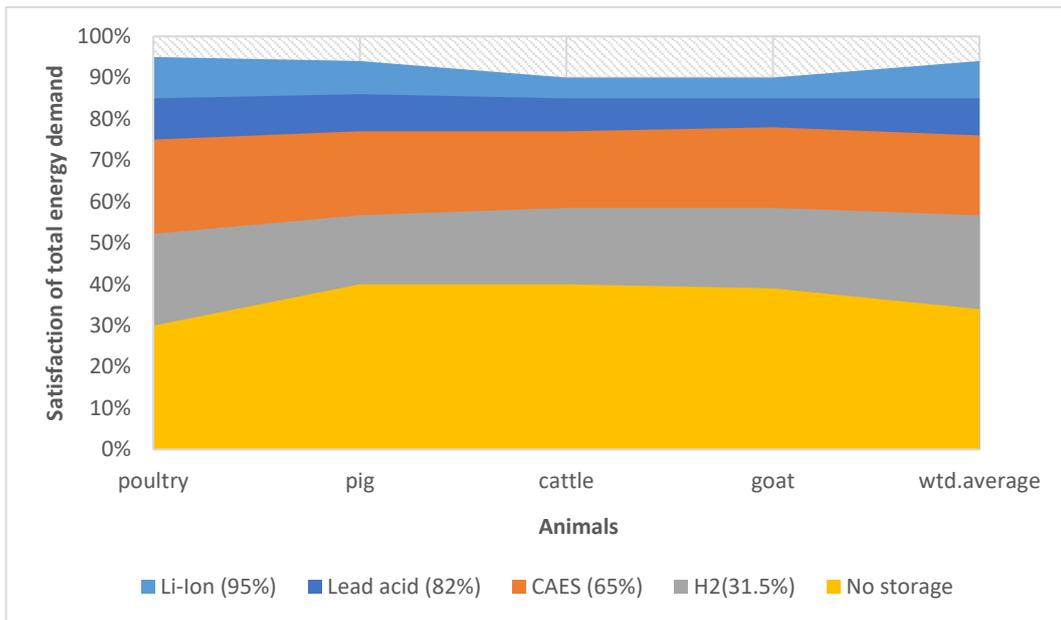


Figure 19 - Benefits derived using different storage system (round trip efficiency)

Figure 19 shows how different technologies improve the level of energy demand satisfaction. The additional satisfaction is strictly related with the round trip efficiency. The higher is the round trip efficiency the higher is demand satisfaction. From an energetic point of view, this solution seems to solve great part of problems related to renewable production, especially using Li-Ion batteries. Anyway, the higher is the efficiency of the storage system the lower is the storage size achievable due to high cost and technical complexity. Now is just presented the energetic benefit but the economic analysis in chapter 5.2 will give a more global perspective, describing the limits of these choices.

4.5 Exploiting biogas energy

The great energy potential contained in the agro-productive sector is biogas. All the bio-waste generated by animals and vegetables can be used as primary resource to generate biogas. What comes out from the precedent chapter is that, the capacity of the storage system to increase satisfaction, is strictly related to its efficiency and size. It is now interesting to see how the situation change exploiting the biogas potential of each animal.

The Biogas Ratio and the fraction of N

Biogas has a double valence. It can be directly burned to produce heating with an indicative efficiency of 90% respect to the LHV or it can be converted in electricity with an indicative efficiency of 30% respect to the LHV. In order to understand how much, biogas can support production, it must be netted of its “average conversion efficiency”.

	Biogas Ratio	Average conversion efficiency	Fraction of N
poultry	0.42	90%	0.38
pig	0.58	60%	0.34
cattle	4	30%	1.25
goat	3.4	30%	1.02

Table 15 – Biogas Ratio, Average conversion efficiency and Fraction of N.

Biogas Ratio is the ratio between total production of biogas and total energy demand over the year. Average conversion efficiency (ACE) represent how efficiently biogas is converted in useful products. Fraction of N is the product between Biogas Ratio and Average Conversion efficiency and represent effectively the contribution of biogas to achieve at least N equal to one.

Cattle and goat have demand exclusively electrical. Their average conversion efficiency is 30%. Pigs demand is 50% heating and 50% electricity. ACE is 60%, supposing that half biogas is converted in heat and half in electricity. Chickens have demand almost exclusively of heating. Their ACE can be considered 90% without appreciable error.

Even having the lowest conversion efficiency, cattle and goat can achieve N equal to one simply using their biogas production. Chickens and Pigs need to produce between 60% and 70% of total demand with other sources.

Benefits derived using biogas

Respectively for poultry, pig, cattle and goat, the presence of Biogas in the energetic mix (keeping the logic $N=1$ without storage) permits to achieve 60%, 67.6%, 100% and 100% (total 69%) satisfaction of energy demand in the year.

Also maximum storage size reduce appreciably moving to peak storage 27700 kWh poultry, 2642 kWh pig and average storage 9290 kWh poultry, 920 kWh pig.

Goat and cattle use only biogas to satisfy demand. Goat consumes all energy produced in the year while cattle have the possibility to produce an extra 25% of its yearly energy demand. This biogas could be exchanged to support other farms (poultry and pig) to satisfy their demand.

Electricity or biogas, the most suitable energy for farms

Precedent chapters permit to make same consideration regarding the most suitable source for each farm. PV panels and wind turbines are not very suitable for poultry and pig farms where demand is strongly characterized by heating and the technology used is based on direct use of electricity for heating. It is necessary to appreciably oversize the plant to have N equal to one and the storage size required is extremely high.

Cattle and goat adapt better to renewables in terms of both plant and storage size. For Biogas is the opposite, the “average conversion efficiency” of *Table 15* shows that poultry and pig converts biogas with higher average conversion efficiencies.

Since the model permit to analyse electricity and biogas exchange between farms, it is interesting to see the evolution of the system in both cases, keeping always the assumption of N equal to one for each farm. The target is always to produce what is required in the year and to satisfy 100% of energy demand.

4.6 Microgrid

The introduction of Microgrids generates several positive effects on the system. Considering the basic case without biogas exploitation and electrical storage, if farms were interconnected, the levels of demand satisfaction would be poultry 51.7%, pig 57%, cattle 57.7%, goat 56.4% and all 54.3 %. Satisfaction increases because increases the probability of matching production-demand.

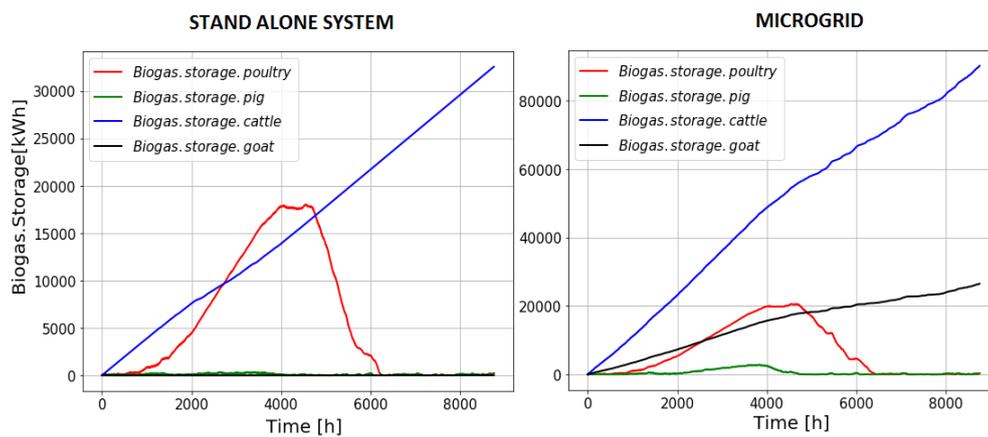


Figure 20 - Evolution of biogas storage with and without microgrid

The situation appreciably improves also considering biogas in the energy mix. It is possible to gain 10% of global energy demand satisfaction interconnecting farms. Poultry moves to 72 % satisfaction and pig achieves 79%. Moreover, at the end of the year, the stock of bio-methane is triplicated for cattle and increases of more than 20000 kWh for goat.

The appreciable increasing in available energy from one case to another is related to the fact that any kWh of electricity for cattle and goat is equivalent to more than three kWh of bio-methane due to their low ACE (see *Table 15*).

As introduced in chapter 4.5 all this “bio-energy” could be transferred to poultry and pig to sustain their energy production

4.7 Bio-methane exchange

Once known the amount of bio-methane available in the Microgrid case, it is interesting to see what happen exchanging it. The logic used for the exchange is described in chapter 2.6. Cattle produce bio-methane up to 1.25 times its demand ($N=1.25$), the excess is accounted to analyse all available potential.

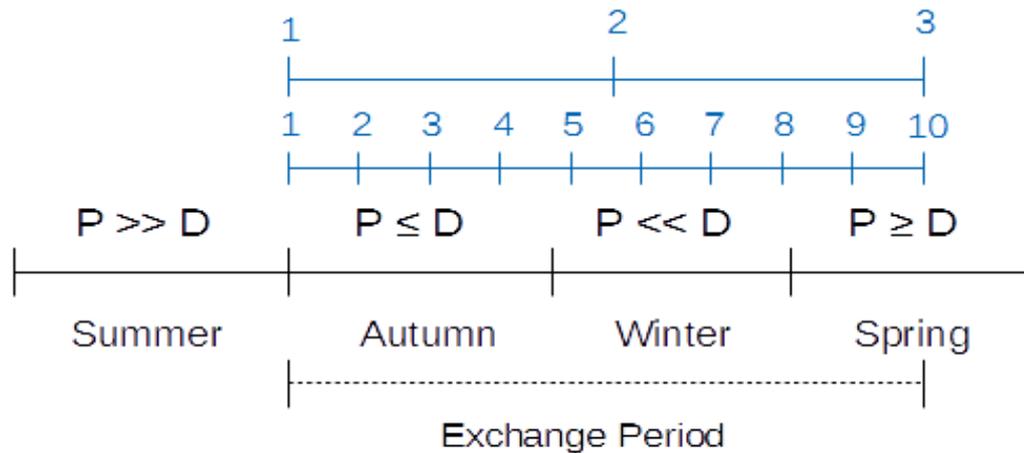


Figure 21 – Logic used for bio-methane exchange

Since the logic is to maximize satisfaction and minimize exchanges, it is important to understand when is more profitable to make the exchange.

Using pipelines, everything can be considered instantaneous and following farms demand. Using trucks is not possible to transfer energy as desired because they require time, technical considerations and costs for any exchange. Since energy cannot be exchanged instantaneously, a criterion must be suitably set. The logic used is to decide the “exchange period” and divide it for the total number of exchanges in order to know when to do it. An example with ten and three exchanges is represented in *Figure 21*.

The exchange period have been set considering that the principal period where demand exceeds production ($D > P$) is between beginning of autumn and first part of spring. Exchanges in summer are not useful and reduce global satisfaction if accounted in the exchange period. It is clearly more profitable to concentrate the total amount of biogas available where there is strong necessity then simply distribute it along the year. [Appendix 4]

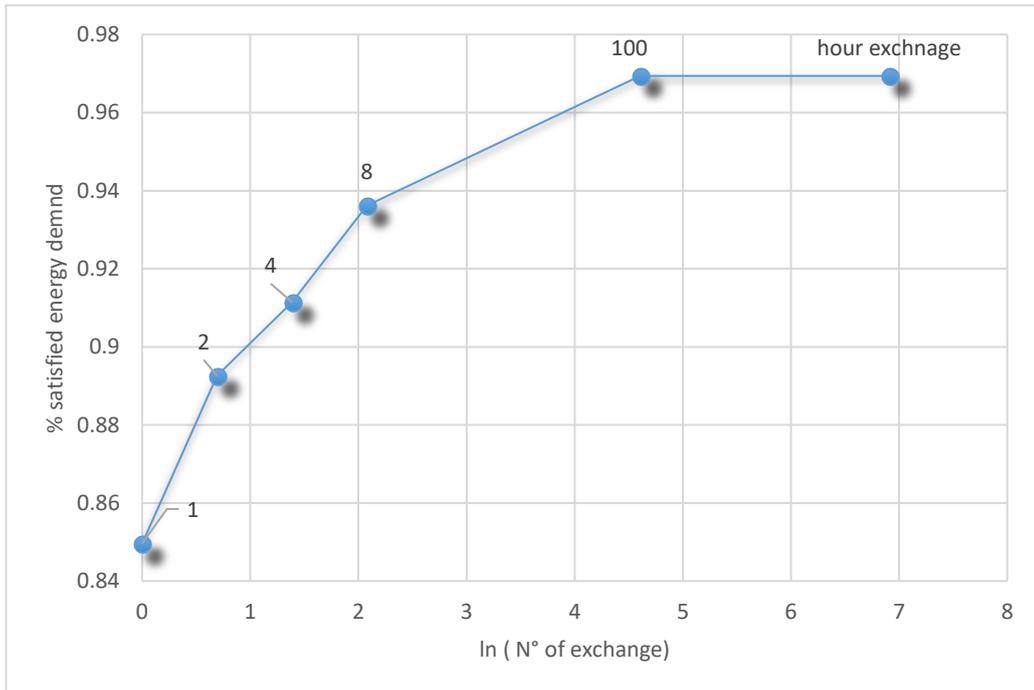


Figure 22 – Global energy demand satisfaction using different number of exchanges

Figure 22 shows the evolution of global energy demand satisfaction with different number of exchanges. The x-axis is described in logarithmic scale to graphically compact the information. Since the total amount of bio-methane available is fixed, it is important to understand when there is not more appreciable relative advantage increasing the number of exchanges. Benefits are evident even making just one exchange. Global satisfaction move from 79% to 85%. Passing from one to eight exchanges is possible to increase energy demand around 10%. From eight on is possible to gain only an additional 3%.

Hour exchange represent the case where bio-methane is exchanged through pipelines. In this case is possible to achieve maximum satisfaction. 100 exchanges are represented to show that over certain values, increasing the number of exchanges is less profitable because the trend starts to decrease drastically up to become horizontal.

NOTE: This analysis does not take into account the energy consumed (fuel) to transfer bio-methane.

4.8 Resume of results

	<i>Renewables</i>	<i>Renewables + biogas</i>	<i>Microgrid (Renewables/ Rnws+biogas)</i>	<i>Microgrid + biogas exchange</i>	<i>Renewables + Storage</i>
<i>poultry</i>	30%	60%	51.7%/72%	98%	95%
<i>pig</i>	40%	67.6%	57%/79%	94%	94%
<i>cattle</i>	40%	100%	57.7%/100%	100%	90%
<i>goat</i>	39%	100%	56.4%/100%	100%	90%
<i>all</i>	34%	69%	54.3%/79%	97%	94%

Table 16 – resume of results, maximum energy demand satisfaction for different plant alternatives

Differently from optimizations, simulation models do not find an optimum but give to the user different scenario alternatives.

What can be deduced from the energetic analysis resumed in *Table 16* is that, energetically speaking, farms contain the potential to be energetically self-sufficient without oversizing energy production. The higher is the complexity of the system the higher will be self-sufficiency.

The simple use of renewables (photovoltaic + wind turbines) permit to achieve just between 30-40% of demand satisfaction. Renewables are not dispatchable and are not able to meet demand any time-step.

Integrating an electrical storage to renewables is an effective solution depending on the round trip efficiency. The result presented in the last column of *Table 15* correspond to the use of Li-Ion batteries that are the most efficient. Using Lead Acid batteries, CAES and Hydrogen storage, self-sufficiency achieve respectively 85%, 76% and 57%.

The introduction of biogas largely improve performance. Cattle and goat can satisfy their entire demand using the electricity produced by biogas. Poultry and pigs can satisfy on between 30% and 40% of their demand using only biogas. What is lacking to achieve N equal to one is composed of Renewables. The combination of Renewables and biogas permit to achieve between 60 and 70% satisfaction.

The introduction of microgrids permit to increase global satisfaction up to 20%. Using microgrids because the possibility that production and demand meet is higher. Moreover, microgrids are essential to permit an effective biogas exchange. In the stand-alone case, cattle and goat consume almost all the biogas produced to

satisfy their demand. Using a microgrid part of their demand is satisfied by renewables and they are able to save higher quantities of biogas useful for the exchange. The level of satisfaction described in the fourth column of Table 16 reflect the case where biogas is exchanged through pipelines in form of bio-methane (biogas must be always upgraded before to be exchanged). If pipelines are not available then the exchange is generally conducted using trucks (see chapter 4.7). Passing from one to eight truck exchanges is possible to improve global satisfaction from 79% to 94% (15% improvement). From eight truck exchanges to pipelines is possible to gain just an additional 3% of global satisfaction. This can be explained because the total amount of biogas available is fixed and the relative advantage reduces increasing the number of exchanges.

4.9 Farm's inside conditions

As explained in chapter 2, the model is not simply used for resource management. It is also an effective instrument useful to understand the internal dynamics of the system and the effects of resource scarcity (see chapter **Error! Reference source not found.**). As described in chapter 2.4, there is a reciprocal connection between energy and food production. Such reciprocity is an exogenous input for the model and can be suitably adapted for any case study of interest. *Anyway, this study did not focus on the analysis of the impact of energy scarcity. Several variable must be taken into account to conduct a realistic analysis. Since this work have not been done, here is just presented an example that shows that the model is effectively able to perform these kind of studies and explains how the analysis can be conducted.*

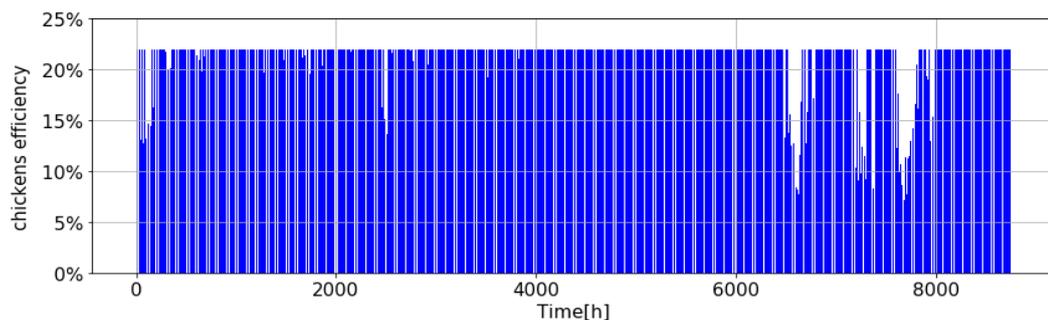


Figure 23 - chickens efficiency variation in the year due to temperature variation

Figure 24 represent internal temperature (T.AdultChickens), external temperature (T.external) and levels of ventilation (right y-axis and green line) for an adult poultry

breeding able to satisfy around 85% of its annual energy demand. T.target is the desired internal temperature.

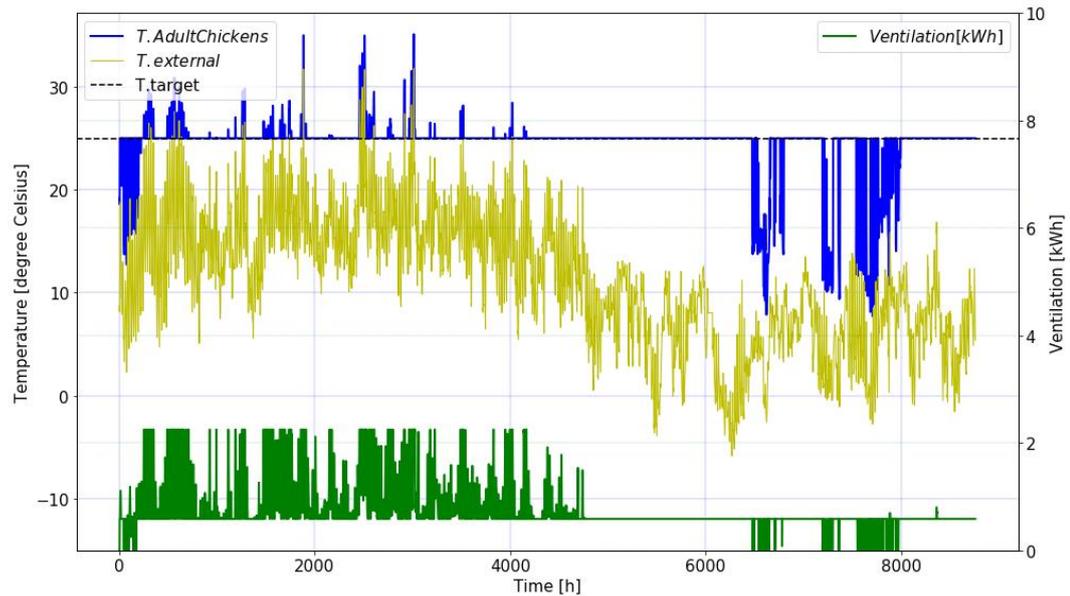


Figure 24 – Evolution of inside temperature and required ventilation in a poultry breeding satisfying 83% of its energy demand

Internal Temperature

Since the farm of *Figure 24* satisfies only 83% of total energy demand, there are periods in the year where temperature drastically reduces up to 10°C (first 1000 time-steps and between 6000 and 8760) because there is not sufficient energy for the heating system. Chickens' production efficiency varies proportionally. (*Figure 23*)

During summer (between 2000 and 4000), internal temperature touch 34-35°C because of inadequate cooling systems. Again, chickens' efficiency is negatively influenced by this condition.

Both situations described are highly dangerous for animals' surviving and cannot be accepted for large number of hours without taking action. Temperature evolution is derived using equations of chapter 2.7

Ventilation

Using the same equations is possible to derive also the recommended level of ventilation during the year (green curve). In reality, ventilation will not drop continuously, but from the simulation is possible to derive optimal average values for any season.

Ventilation is the only cooling system available. During summer, even using maximum levels of ventilation, is not possible to bring internal temperature to the target level. In this case could be useful a cooling system based on water spreading, nebulizers or simple water pumping.

Animal Load

Another solution in summer could be to reduce the animal load (ρ). Less animals at parity of space available produce less heat that is easier to manage.

Anyway, following the same reasoning, lower animal load implies higher heating demand in wintertime.

Relative Humidity

It possible to see that minimum levels of ventilation are always present during the year, even when internal temperature is very low. Ventilation, in fact, is not used only for thermal regulation but also for air recirculation and humidity control. For this reason, ventilation cannot be off-mode for more than few hours.

Evolution of relative humidity inside the farm have not been studied in details. The assumption is that minimum levels of ventilation are sufficient to keep acceptable values of relative humidity (R.H).

After a more general discussion on the principle variables characterizing well-living and correct production inside the farm, it is presented a list of interesting parameters, opportunely selected for the considered animals, which gives a more compact information respect to the precedent graphs. Energy demand satisfaction considered is Poultry 83%, Pig 82% Cattle 80% Goat 80%.

Looking at *Table 17* is possible to see that even a plant able to satisfy around 80% - 85% of energy demand generates several production difficulties. For poultry up to 1206 h in the year, have target temperature not respected. It is interesting to see also the number of consecutive hours where target temperature is not respected. Few consecutive hours probably do not affect animals well living but here the number is 94, clearly not acceptable. Ventilation is even less flexible than temperature. Without recirculation of air, internal conditions could degenerate rapidly and 12 consecutive hours could be dangerous for animals' life.

Similar considerations can be done for chicks and pigs in all life stages. Nursery pigs use infrared heaters for heating, than the interest focus on the number of hours without infrared heaters. Cattle and goat peak demand is in summer, where also production touch its peak.

<i>N° hours T.in < T.target</i> chicks	832
<i>N° max consecutive hours T.in < T.target</i> chicks	50
<i>N° hours T.in < T.target</i> chickens	1206
<i>N° max consecutive hours T.in < T.target</i> chickens	94
<i>N° hours without ventilation</i> chickens	92
<i>N° max consecutive hours without ventilation</i> chickens	12
<i>N° hours without infrared heaters</i> lactating pig	151
<i>N° max consecutive hours without infrared heaters</i> lactating pig	60
<i>N° hours T.in < T.target</i> nursery pig	2104
<i>N° max consecutive hours T.in < T.target</i> nursery pig	415
<i>N° hours without ventilation</i> growing pig	562
<i>N° max consecutive hours without ventilation</i> growing pig	40
<i>N° hours without milk refrigeration</i> cattle	1345
<i>N° max consecutive hours without refrigeration</i> cattle	68
<i>N° hours without milk refrigeration</i> goat	921
<i>N° max consecutive hours without refrigeration</i> goat	44
<i>N° hours T.in >Tmax</i> cattle	14
<i>N° hours T.in >Tmax</i> goat	18
<i>Average annual efficiency</i> poultry	0.209
<i>Average annual efficiency</i> pig	0.159
<i>Average annual efficiency</i> cattle	0.179
<i>Average annual efficiency</i> goat	0.179

Table 17 – Suitable indicators to understand the proper functioning of the production process.

Just for few hours in the year limit temperatures are not respected, In fact average efficiency in the year lose just 0.1%. Poultry and pig lose around 1-2% of efficiency as average in the year.

Another good index to understand correct production in cattle and goat farms is the number of hours without refrigeration. For both animals, for more than 1000 hours there is no energy for refrigeration with “max consecutive hours” around 100 hours. This means that even if animal’s production is maximum, there is no energy to keep the product fresh.

Economic considerations

To evaluate the economic performance of the farms is not purpose of this study. Anyway, a little excursus is interesting to understand the effects of partial satisfaction of energy demand on the economy of the farm.

Considering poultry production, from *Table 17* is possible to see that the annual efficiency reduces of almost 1% in the year (from 22% to 20.9%).

Every day 1% efficiency correspond to 7 kg chicken’s meat. Price estimation for whole boilers in Europe is 1.75 €/kg [58]. This means that in 1 year (365 working days) around 4500 € are lost. This simple calculation shows the importance of a correct energy supply inside the farm.

5 Results - economic analysis

Results of chapter 4 concluded with an optimistic scenario. Using different plant alternatives is possible to achieve almost 100% of energy demand satisfaction.

This chapter aims to describe results from an economic point of view, to evaluate the affordability of choices made and to analyze technical difficulties and limits that compromise the success of the investment.

The simulation model by itself is not able to perform an economic analysis but gives all important information necessary to do it (size of plant, size of storage, levels of satisfaction in different configurations, relative advantage of energy exchange....etc.). If opportunely combined with other instruments (Microsoft excel in this case) an economic analysis can be performed.

Size of results – additional technical considerations

<i>(Renewables / Res + biogas)</i>	<i>poultry</i>	<i>pig</i>	<i>cattle</i>	<i>goat</i>
<i>Wind turbines [kW]</i>	150/90	105/65	30/0	15/0
<i>Photovoltaic [kW]</i>	75/45	55/35	15/0	7/0
<i>Biogas [kW]</i>	14	14	28	11
<i>Peak demand [kW]</i>	75	30	8.5	4
<i>Storage power [kW]</i>	140	85	24	12
<i>Peak storage [kWh]</i>	70800	20700	4320	2030
<i>Energy to Power ratio [h]</i>	505	243	180	170

Table 18 – Size of power plant, storage system and peak demand obtained in results

Peak Power installed is around 5-9 times higher than peak demand in the case without biogas (Renewables) and is able to satisfy only 30-40% of energy demand without storage. This condition is clearly not favorable because means that minimum power installation able to satisfy 100% of energy demand should be around 15-27 times the peak demand.

Using biogas (Res+biogas), the situation slightly improves. Power installed now is between 2-6 times higher than peak demand and the plant is able to satisfy between 60-100% of energy demand. The reason of such improvement can be found looking at the yearly production per kW of each technology. Respectively, 1

kW of wind turbines, photovoltaic and bio-digester produces 1075 kWh_{el}, 1145 kWh_{el} and 2630 kWh_{el}.

Moreover, biogas production is more dispatchable and is not function of climate conditions. Wind turbines are the most disadvantaged since Île-de-France location is a low wind region.

The voice “storage [kW]” represent the minimum power that must be installed to ensure that all energy is correctly stored. It is derived calculating the maximum delta between production and demand for any animal. That value is valid for all storage technologies considered.

The difference between kW and kWh required is quite large, the energy to power ratio required is higher than 150 h for any animal considered. This can be explained because, independently from the typology, farms does not require more than 45 kW any hour. On the other hand, the storage system must be able to store all the energy (not directly consumed) produced in the year by a power plant sized with N equal to one.

At the light of these considerations, it is now interesting to study the economic implications of the different plant alternatives described in chapter 4.

Introduction to the economic analysis

Based on the LCOE analysis, the economic analysis will keep as reference the plant alternatives used in the energy analysis but will keep also the possibility to sell energy to the national grid. In particular will be always preferred to consume energy respect to inject it.

The principal objective remains self-sufficiency but it has been considered interesting to analyze all possible alternatives to recover the investment.

Power Plants will be compared using the NPC and LCOE. Storage systems will be compared using the LCOE since their only benefit is the stored electricity. A simple cost-benefit analysis will be preferred for bio-methane exchange.

It is here resumed what benefits and costs are considered in the economic analysis.

- **Benefits:** avoided cost of electricity, avoided cost of methane, feed in tariff of each technology and subsidies for anaerobic digesters.
- **Costs power plant and storage system:** investment costs, O&M costs and replacement costs + additional plant costs due to storage losses and storage losses costs.
- **Costs energy exchange:** see *Table 11*

Costs of electricity and methane is considered constant during the project lifetime. Discount rate (r) is 5% always. This value comes from ceicdata website [48] where is shown that in the last 30 years French discount rate have averaged around 5%. It is considered the same average in the next years. Project lifetime for NPC and LCOE calculation is 25 years always. No salvage considered.

Brief description of next chapters

- Chapter 5.1 describes the NPC of the power plant with and without biogas for any animal considered. The objective is to have NPC at least equal to zero.
- Chapter 5.2 describes the LCOE of all storage systems and animals considered and describes in detail the principal voice of cost of each technology. The objective is to understand if the introduction of the storage system can increase the affordability of the investment.
- Chapter 5.3 describes costs and benefits of bio-methane exchange, explaining what are the principal limits of this choice.

LCOE and national costs

	<i>LCOE</i>	<i>f.i.t - LCOE</i>	<i>n.c - LCOE</i>	<i>unit of m.</i>
<i>Wind turbines</i>	0.137	-0.05	0.013	€/kWh _{el}
<i>Photovoltaic</i>	0.122	0.018	0.028	€/kWh _{el}
<i>λ = 0.35</i>	0.132	-0.032	0.018	€/kWh _{el}
<i>Biogas electricity</i>	0.195	-0.015	-0.045	€/kWh _{el}
<i>Bio-methane</i>	0.059	0.035	0.011	€/kWh

Table 19 - LCOE respect to feed in tariff (*f.i.t*) and national cost (*n.c*) for each technology considered.

Before to analyze the affordability of the plant alternatives described in results. It is interesting to have a look on the LCOE of each technology. The LCOE of the different storage systems will be presented in chapter 5.2 in separated analysis. Photovoltaic seems the best alternative, but as explained in chapter 2.9, LCOE permit to compare the plants just partially. What is deducible here is just that in order to recover the investment, photovoltaic needs lower revenues per kWh. If the purpose is to sell electricity to the national grid, the most advantaged is Photovoltaic that has highest difference between feed in tariff and LCOE. Follow

biogas and wind turbines. " $\lambda=0.35$ " represent the optimal plant found in the energy analysis (chapter 4.3).

If the purpose is to be energetically self-sufficient and off-grid, then photovoltaic or wind turbines alone permit to achieve only between 24% and 28% of global satisfaction. In fact, in the energy analysis they have been opportunely combined to maximize satisfaction. Biogas alone achieve around 55% global satisfaction with 100% for cattle and goat.

Except for biogas electricity, it is always more convenient to internally consume energy respect to inject it into the national grid. In terms of avoided cost of energy, any kWh of electricity cost 0.15 €/kWh while methane 0.07 €/kWh. Supposing for a moment that all plants are able to satisfy 100% of energy demand. Photovoltaic and wind turbines can recover the investment only if the entire demand is composed of electricity. Revenues from methane are lower than their LCOE. On the contrary, biogas can be converted in electricity or be accounted as bio-methane at LCOE lower than national cost.

What optimistically arise from the LCOE analysis is that a positive investment is not an absurdity. The real difficulty is to be off grid. PV panels and Wind turbines can generate electricity at prices lower than national one but they are able to satisfy only 30-40 % of demand. Biogas is a positive solution for poultry farms where demand is almost exclusively heating, but the energy contained in the manure is not sufficient for more than 40% of demand.

5.1 Power plant: costs and benefits

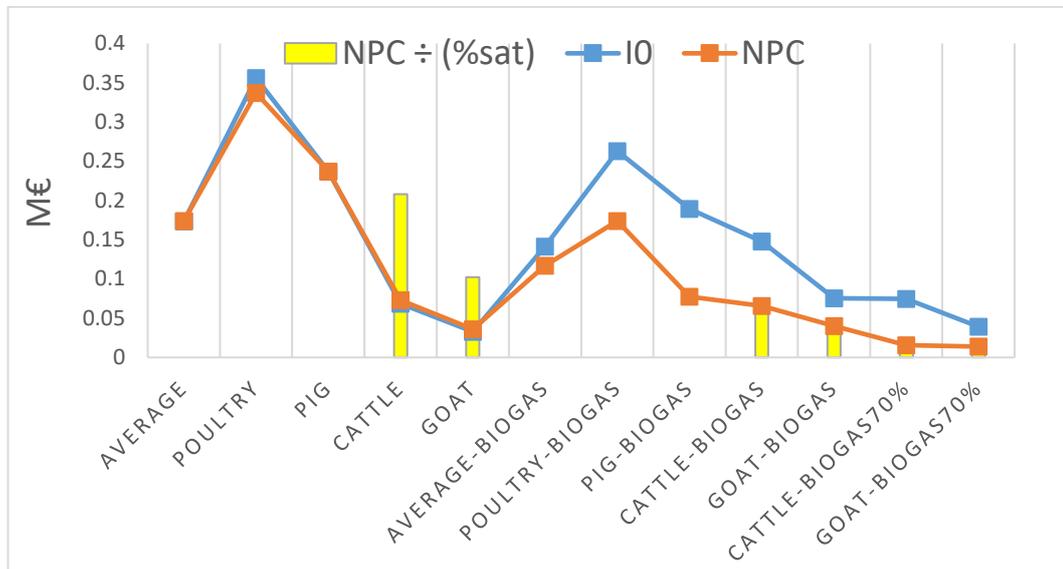


Figure 25 - initial investment and NPC of all farms considered in different plant alternatives with incentives.

The simple name of the animal represent the plant with only PV panels and Wind turbines. "-BIOGAS" stands for plant with biogas in the energy mix" and "-BIOGAS 70%" represent the case where biogas plant receive subsidies for 30% of the investment cost. "NPC ÷ (%sat)" represent the ratio between NPC and the percentage of satisfaction achieved by that plant. For cattle and goat, NPC with and without biogas is similar only if the electricity not consumed is sold at feed in tariff. Dividing for the percentage of satisfaction permit to normalize results respect to an off-grid solution. Majority of Investments have positive trend (NPC lower than IO) but no one achieve NPC equal to zero.

Cattle and goat without biogas could achieve NPC equal to zero only satisfying 95% of demand and without additional costs. Poultry and pig cannot achieve NPC equal to zero. In these terms, the simple introduction of Microgrids does not change the situation appreciably since it permits to achieve satisfaction levels just around 52% and implies additional costs.

The introduction of biogas in the energy mix generates several positive effects. Poultry and pigs halve their NPC and the distance between IO and NPC increases appreciably for all animals, meaning that investment trends are largely more positive. If cattle and goat receive subsidies equal to 30% of investment cost, they can almost recover the investment.

Unfortunately, even in this optimistic scenarios, no farm is able to achieve positive investments. All other cases where there are no incentives or farms decide to be completely off-grid will be clearly less affordable. Energy self-sufficiency in geopolitical contests like Île-de-France, where energy is guaranteed and still sold at relatively low national prices, is possible energetically but is still an economic challenge.

At the actual state, for any farm is more convenient to internally consume biogas and electricity. Incentives for any kWh of bio-methane or electricity injected could seem an attractive solution but the difference between the benefits derived from injection and the cost for any energy unit consumed moves around 2-3 c€/kWh.

To consume biogas and electricity internally, permit to recover the entire cost of energy absorbed by the national grid (7-15 c€/kWh). Farms in fact are not only producers of energy but also consumers.

At the light of the present analysis, a support scheme for any kWh of biogas internally consumed could be studied. For example, if any kWh of electricity generated by biogas plants was remunerated 0.02 €/kWh, cattle and goat would be able to have NPC equal to zero.

Incentives are not the only possibility of improvement. Storage systems and bio-methane exchange could become an effective solution.

5.2 Storage system: costs and benefits

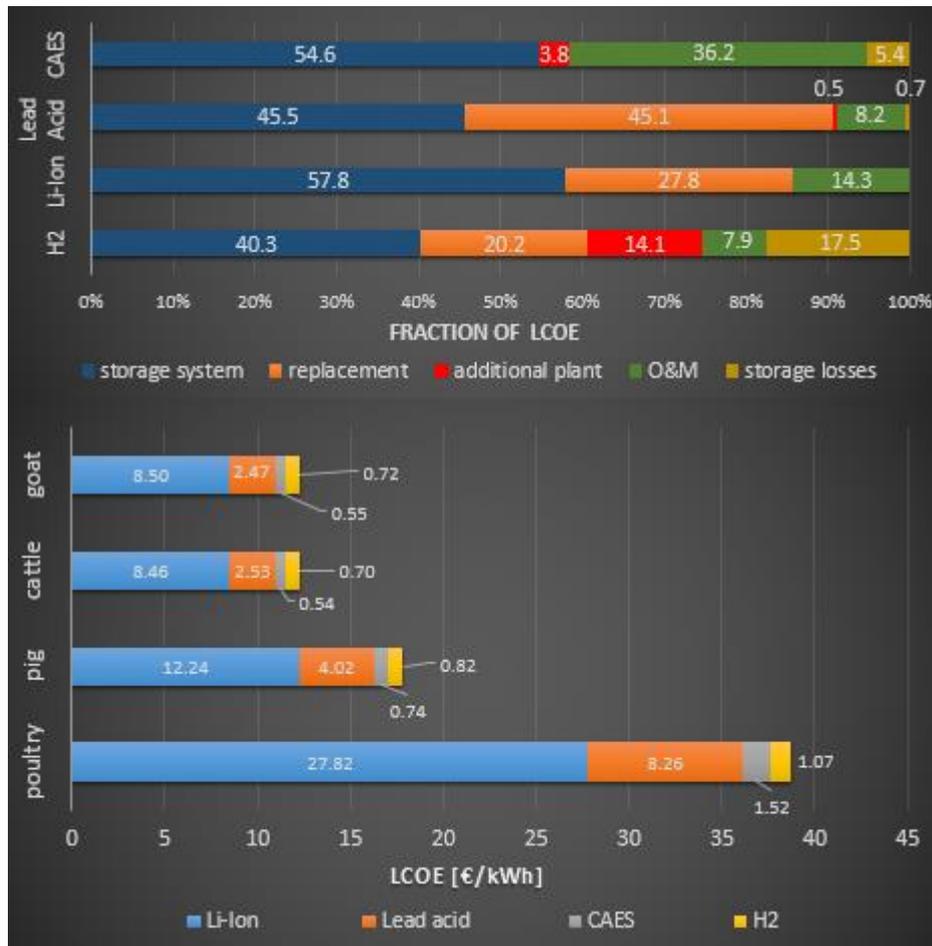


Figure 26 – NPC and cost sharing of the storage system alternatives

All technologies presented in 3.3.2 are compared here in terms of LCOE and are all sized to achieve 100% self-sufficiency.

As it is possible to see in the bottom part of Figure 26, costs increase proportionally to the peak storage required (see Table 18). Poultry is the most disadvantaged, largely distant from the other animals. Follow pig, cattle and goat (Figure 18). It is again presented the difficulty to sustain self-sufficiently an energy demand based on heating with direct use of electricity. The high peak storage required brings any storage system installation to be difficult to implement for poultry and pig while cattle and goat seem more adaptable.

In terms of technologies, batteries are the most disadvantaged but the cost difference respect to the other two technologies reduces with respect to the size

of the storage. This means that they are more influenced by the size of the storage required. This difference can be explained considering that CAES and PEMFC have Energy to Power ratio (E/P) higher (or in the same range) than the one required by the farms while for batteries it is largely lower (*Table 9*). CAES and PEMFC install only the number of kW required by any storage system its the proper functioning while batteries install at least between 17 and 50 kW per kW required, depending on the animal.

Batteries cost per kWh is the highest, especially for Li-Ion, and the high E/P required (*Table 18*) implies technical difficulties, oversizing and underuse of these technologies.

For CAES and PEMFC, costs per kWh can be two order of magnitude lower. Moreover, since the number of kW required is largely lower respect to the number of kWh, both technologies take advantage of this situation and reduce costs of turbines, compressors, fuel cell stack and electrolyser. This double advantage, bring these two solutions to be more competitive and suitable for these kind of applications even having lower efficiency compared to batteries.

CAES system has the lowest NPC for any animal but the difference with hydrogen reduces increasing the size of the storage. Turbines are cheaper than fuel cell stacks at parity of kW installed but O&M costs are higher, losing the advantage for larger plants.

The upper part of *Figure 26* shows better strength and weakness of each technology. The voice "storage system" represent total installed cost, "replacement" is replacement cost, "additional plant" is the cost of additional plant that must be installed to recover losses in the storage process, "O&M" is operating and maintenance cost and "storage losses" is the cost of all energy destroyed to store it. Evaluated at the LCOE of the renewable plant.

Both batteries have almost exclusively costs related to installation and replacement. O&M is the third voice of cost. Lead Acid batteries are able to reduce their O&M respect to Li-Ion thanks to their lower power density, which permits them to reduce the number of kW installed. Both technologies minimize additional plant and storage losses thanks to their high efficiency.

CAES has as principle voices of cost installation and O&M. Costs related to additional plant, and losses are not so relevant because round trip efficiency is not so low for this technology. No replacement considered. PEMFC systems have 30% of NPC related to storage losses and additional plant due to the low round-trip efficiency, which can be considered the real weakness of this technology. O&M are not so relevant while replacement account for 20%. Fuel cell stacks in fact have an

expected lifetime of 10 years. A way to increase round trip efficiency could be to directly burn hydrogen for heating applications and avoid the fuel cell efficiency. Independently from all considerations made, at the actual state no storage system generates positive investments. The cost for any kWh stored is always higher than the avoided cost of electricity. To use electrical storage for poultry and pig demand generates several energy losses, enormous costs and incorrect use of energy. Cattle and goat have negative performances but their demand is more suitable for electrical storage. CAES and PEMFC are more suitable for long time storage as the one required thanks to their high E/P but their low efficiency is a strong disadvantage.

In terms of efficiency, batteries are largely better (especially if compared to PEMFC) and permits a more rational use of energy but the cost for producing energy is always lower than the one to store it. For this reason, batteries cannot take a real advantage with their efficiency.

	<i>Batteries</i>	<i>PEMFC and CAES</i>
<i>Pros</i>	<ul style="list-style-type: none"> - Higher efficiency - Consolidated technology - Expected reduction of costs 	<ul style="list-style-type: none"> - High E/P that permits to largely reduce cost
<i>Cons</i>	<ul style="list-style-type: none"> - low E/P that reduce the adaptability of this technologies in this kind of application - High cost per kWh 	<ul style="list-style-type: none"> - Need still to penetrate the market - High cost of the power unit - Geologic dependence - Lower efficiency

Table 20 – Comparison between batteries, CAES and hydrogen storage

Following IRENA forecasts [34] batteries are expected to largely reduce their price and increase their lifespan in the next years. The other two technologies need still to penetrate in the market and their future is more uncertain. Reduction of costs will be determinant to increase the competitiveness of batteries but the low E/P remains a predominant variable that largely disadvantage them in this kind of application.

5.3 Bio-methane exchange: costs and benefits

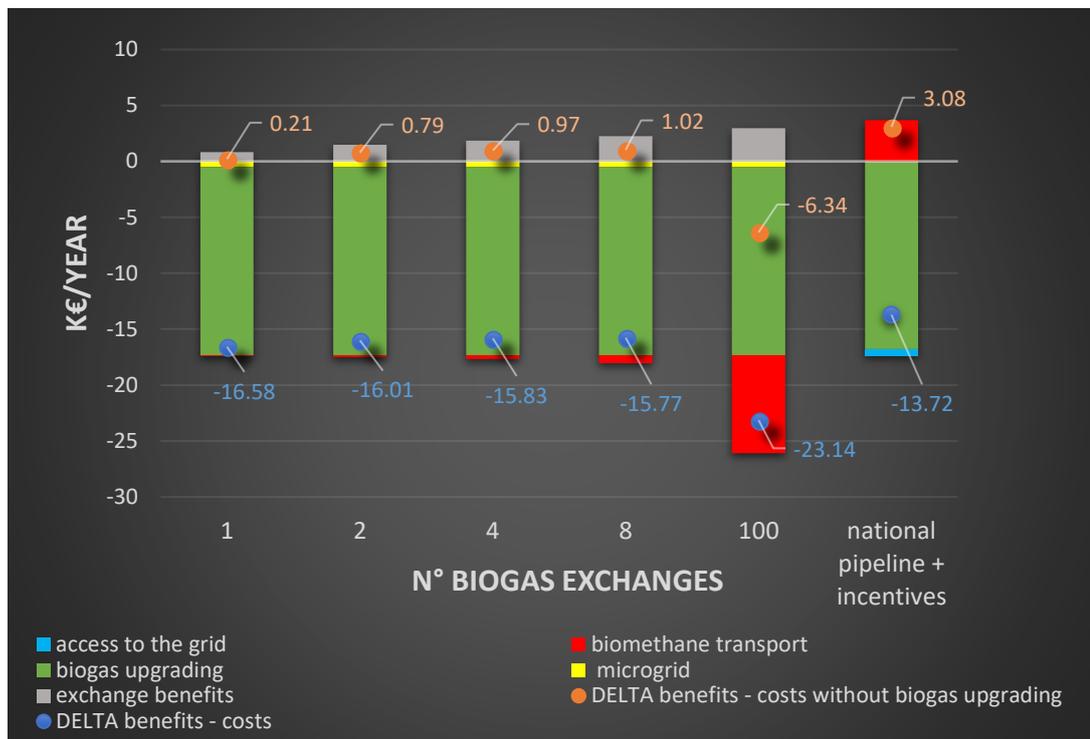


Figure 27 – Benefits and costs of energy exchange

Bio-methane exchange have been analyzed using a cost-benefit analysis in the year. This analysis in this case is sufficient to give all principal information and does not need to be integrated of a NPV analysis.

“access to the grid” is the cost necessary to connect the plant to the national pipeline in case of injection. “biogas upgrading” is the cost of the upgrading plant necessary to convert biogas in bio-methane. “bio-methane transport” is the cost or benefit derived from the transport of bio-methane. Biomethane transport implies costs if exchanged through truck while implies benefits if injected in the national grid because of its feed-in tariff. “exchange benefits” is the benefit derived from bio-methane exchange through truck. “microgrid is the cost of the microgrid necessary to increase the amount of bio-methane available for the exchange (see chapter 4.6).

Looking at the delta benefits-costs the balance is largely negative in all configurations. Looking at the delta benefits-costs without upgrading is the opposite, except for the case “100 exchanges”. The economic benefit derived from the exchange reflects the energetic one described in chapter 4.7. Increasing the

number of exchanges, the relative benefit reduces up to become horizontal while costs increase always more. Since around 8 exchanges the trend is already almost horizontal, 100 exchanges is clearly a negative situation.

What can be deduced in *Figure 27* is that the principal limitation for biomethane exchange and injection is the upgrading. These kind of plants in fact are very expensive especially in small-scale applications. In the case of injection to the national grid, another limit stands on the fact that farms are at the same time producer and consumer of methane. This means that is not possible to gain the entire feed in tariff but just its difference with the national cost (0.025 €/kWh respect to 0.095 €/kWh). Considering the entire feed-in tariff the cash flow moves from -13.7 to -3.4 k€/y. These kind of investments today are more recommended for big plants of 100-300 Nm³/h, which permit to cut upgrading cost [72]. Here the attention focus on farm scale plants with production that moves around 3-5 Nm³/h. If in the future will be possible to cut costs of upgrading also for small plants, this solution could become more affordable.

6 Conclusions

Conclusions on the model

The model seems to well doing its simulation job. It has represented the level of energy demand satisfaction, the evolution of the storage system, the amount of biogas produced and consumed and the effects of the energy exchange in any scenario proposed. The approach based on engines permits to manage a complex system, characterized by resource conversion, recycling, storage and exchange between a high number of agents in a compact and easy way. Keeping at the same time a relatively high number of details. Since either energy production, demand or the animals 'efficiency function are exogenous inputs, the accuracy of results is directly proportional to the accuracy of equations, data and parameters used.

Its weakness emerges when an optimization is required; for example, the calculation of the optimal coupling factor λ required several running and permitted just to approximate its value.

In terms of farms production, even if the case study have not focused on it, it has been shown that is possible to analyze the impact of incomplete satisfaction of energy demand on the animals' efficiency and to extract indicators able to explain the criticality of system conditions. Impact of resource scarcity is another important aspect for future development. The analysis of the impact requires several considerations regarding probability of unfilled demand, thermodynamic of the system, humidity control, animals' behavior...etc. It is important to formalize the problem to find a good compromise between accuracy of results, complexity of the system and effective limits of the model.

The adaptability to other productive systems as agriculture and fisheries is also an interesting future study.

Economy is the second weakness. The model gives all the technical information required to perform an economic analysis but is not able to perform it by itself. An economic analysis requires the support of additional tools (excel in this case).

Finally more advanced and accurate algorithms to describe the energy exchange can be developed.

Conclusions on the case study

What can be deduced analyzing results is that the possibility of self-sufficiency is function of several aspects.

- **Typology of demand:** A solution based on photovoltaic and wind turbines and direct use of renewable electricity to produce heat in poultry and pig farms is very hard to achieve and requires enormous oversizing in terms of both power plant and storage system. On the contrary, cattle and goat achieve good performances and selling the electricity not consumed to the national grid, they can almost recover the investment but the complete self-sufficiency is still hard to achieve.
- **Production of Biogas:** The possibility to be self-sufficient is strictly related to the amount of biogas internally producible. Cattle and goat produce sufficient energy to satisfy 100% demand even using 30% conversion efficiency. Poultry and pig, using higher efficiency are able to satisfy just 30-40% of their demand.
- **Storage system:** Solutions based on batteries, even if more efficient, result very difficult to implement because the Energy to Power ratio required is very high for any animal considered. Solutions based on fuel cells and CAES systems can take advantage of their high E/P, but not sufficiently to recover the investment. The cost for storing one kWh is always higher than buying it from the national grid.
- **Energy exchange:** Energy exchange seems to be essential if the purpose is to be self-sufficient minimizing energy produced. Bio-methane exchange is more effective than microgrids but they must be combined to maximize satisfaction. What really limits this solution is the upgrading of biogas because requires large investments.
- **Climate conditions:** Wind speed and radiation available characterize energy production. Île-de-France is a low wind region and wind turbines result least favorably placed. External temperature direct influence heating and cooling demand. Cold regions as Île-de-France have high heating demand in winter.

In general terms, what can be said is that while energetically is possible to achieve self-sufficiency equalizing yearly production and demand ($N=1$), economically it is still a great challenge. Reduction of costs and more suitable incentives will play a fundamental role to overpass the economical barrier still present. Units of energy internally produced or stored needs to be better remunerated to generate positive

investments. Technological innovation and variety of solutions are also extremely important in these terms.

These kind of solutions today seems more adapted to rural contexts devoid of national grid but the emerging policies, the always-lower cost of distributed energy and the world political instability could bring the centralized system to become less competitive in the next years.

Suggestions for improvement

Once that the situation is clear both in energetic and the weak points of the system have been discovered. It is possible to suggest some solution to improve system performance.

- **Heat Pumps** Heat pumps today achieve COP between 4 and 6. With indicative costs that could varies between 200 and 1100 €/kW depending on the technology and application [49]. An evaluation of benefits and costs would require a more detailed analysis but a simple comparison could be made in order to understand the impact of this technology. As rough estimation, the use of heat pumps with COP = 4 in farms supplied only with electricity, would permit to reduce the size of the renewable plant from 225 kW to 60 kW for poultry and from 150kW to 94kW for pig. Energetically this is always a good solution while economically everything depends on the performance and cost of the heat pump. Another advantage of heat pumps is that can be used also for cooling applications in summertime.
- **Pre-heating of air** If the external air used for internal air recirculation were pre-heated before to be introduced in the building, heating demand would reduce appreciably. Heat could be recovered by the anaerobic digester, CAES systems or inside air.
- **Incentives for self-sufficiency targets** The principal limit of the project stands on costs. Incentives for electricity stored or internally consumed for self-sufficiency targets could largely improve affordability.
- **Centralized Biogas production** Instead of producing in loco with small plants, all manure could be transported to a big plant where could be combined with other vegetables products to increase biogas yield. Farms characterized by electricity demand could be interconnected in a microgrid and supplied by biomethane turbines. The reduction of costs for upgrading and the higher quantities of biomethane generated will bring to cheaper and more effective exchanges. Total plant cost could reduce because of the economy of scale, but complexity and O&M costs will increase appreciably.

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Appendix 1

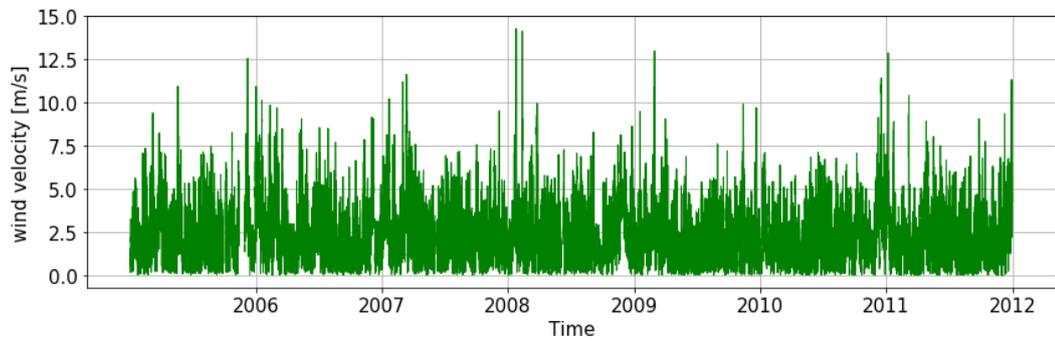


Figure 1 – Wind velocity for any year considered, height 10 m

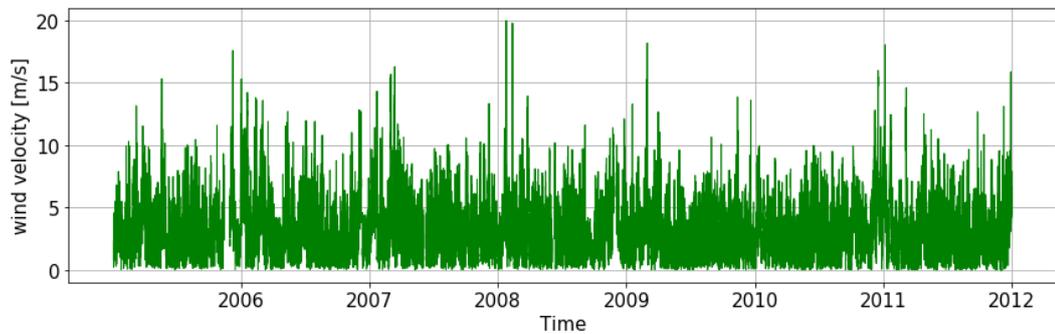


Figure 2 – Wind velocity for any year considered, height 80 m

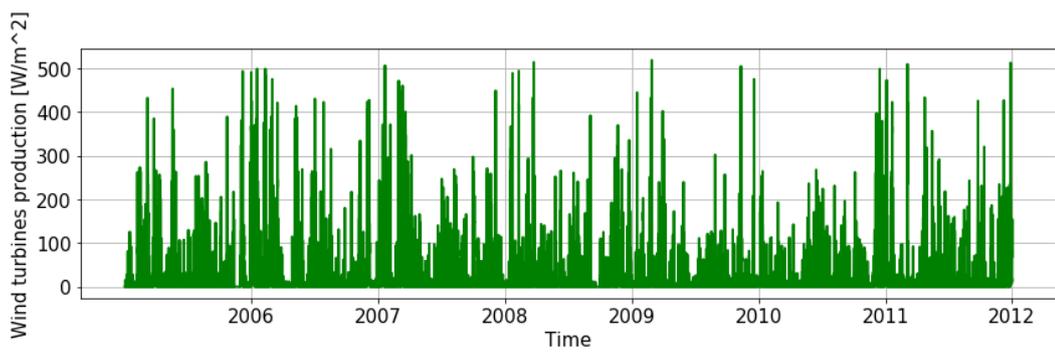


Figure 3 - Wind Turbines power production for any year considered

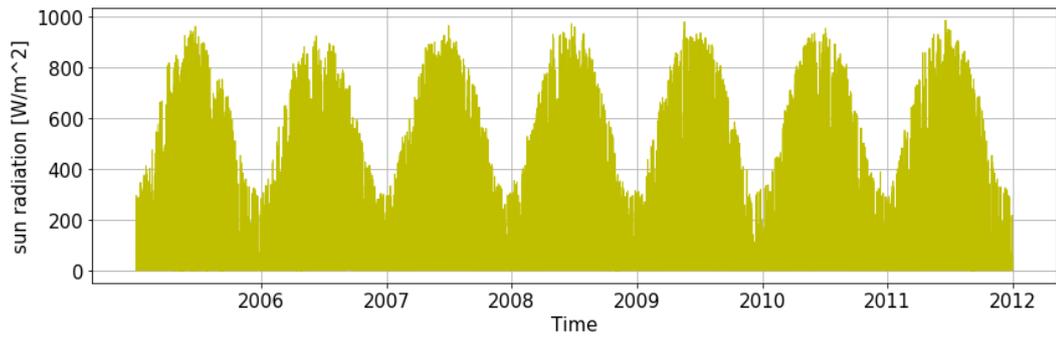


Figure 4 - Sun radiation for any year considered

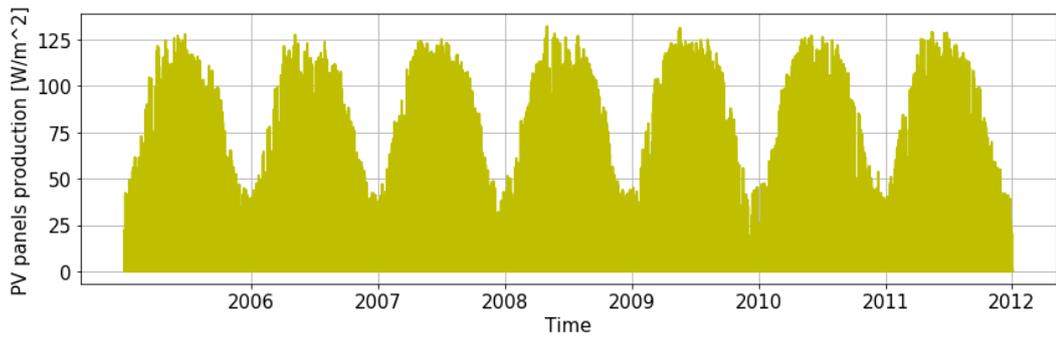


Figure 5 – PV panels production for any year considered

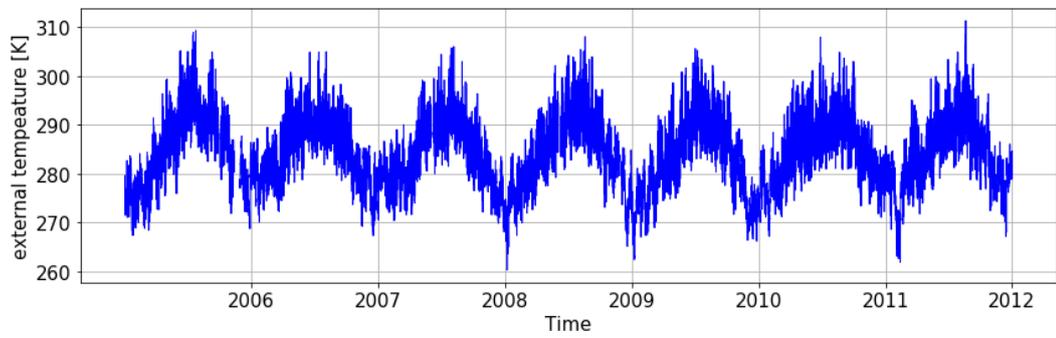


Figure 6– External temperature for any year considered

Appendix 2

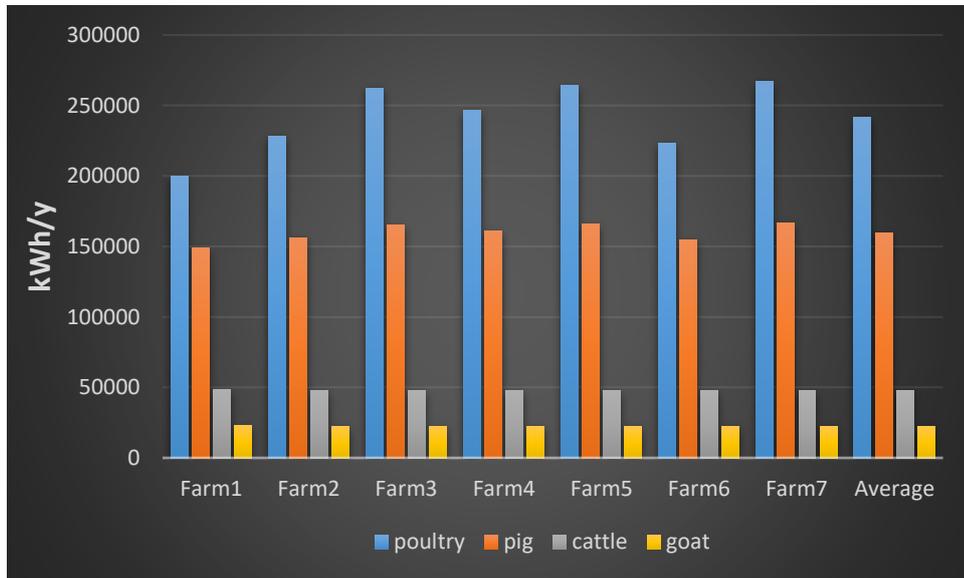


Figure 5 – Total energy consumption for the 28 farms considered

Appendix 3

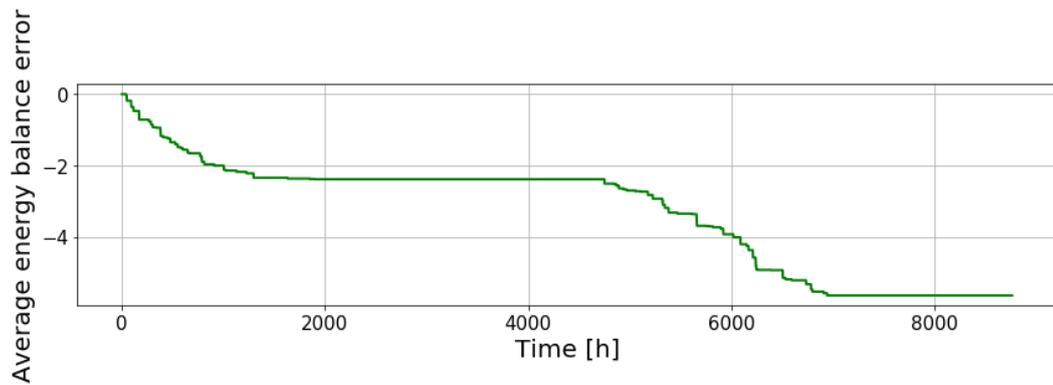


Figure 6 – Average cumulated error of the energy balance in the year (Max error achieved)

Appendix 4

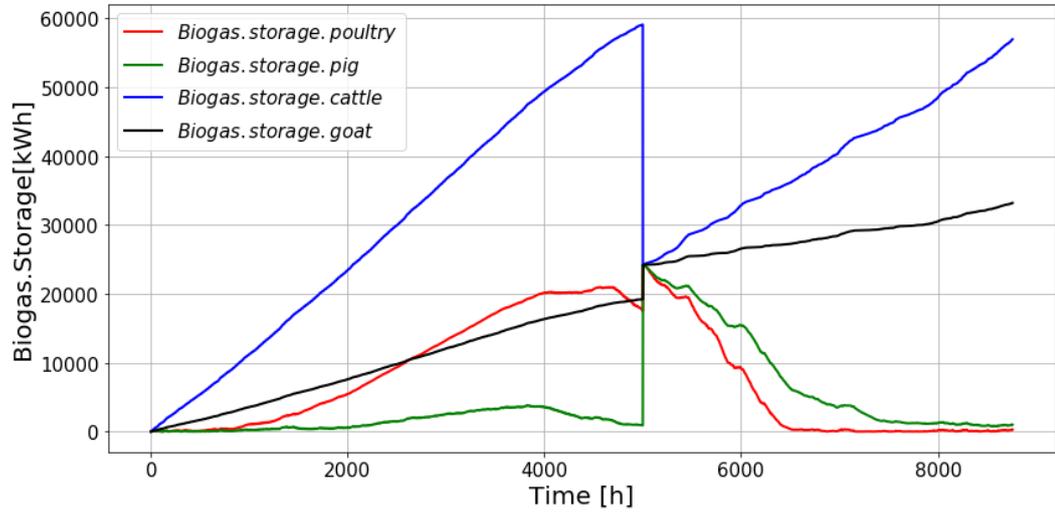


Figure 7 – Evolution of the biogas storage of any animal with 1 exchange

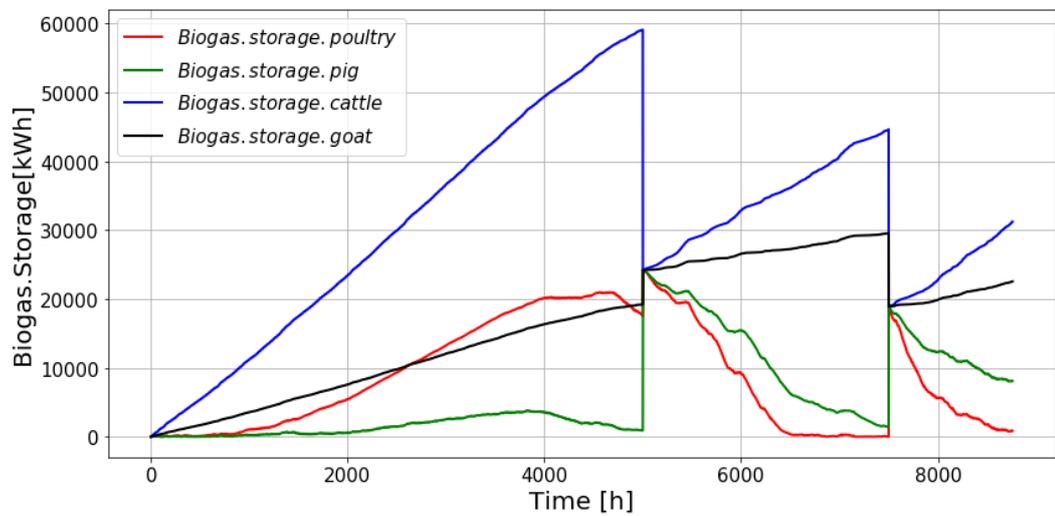


Figure 8 – Evolution of the biogas storage of any animal with 2 exchange

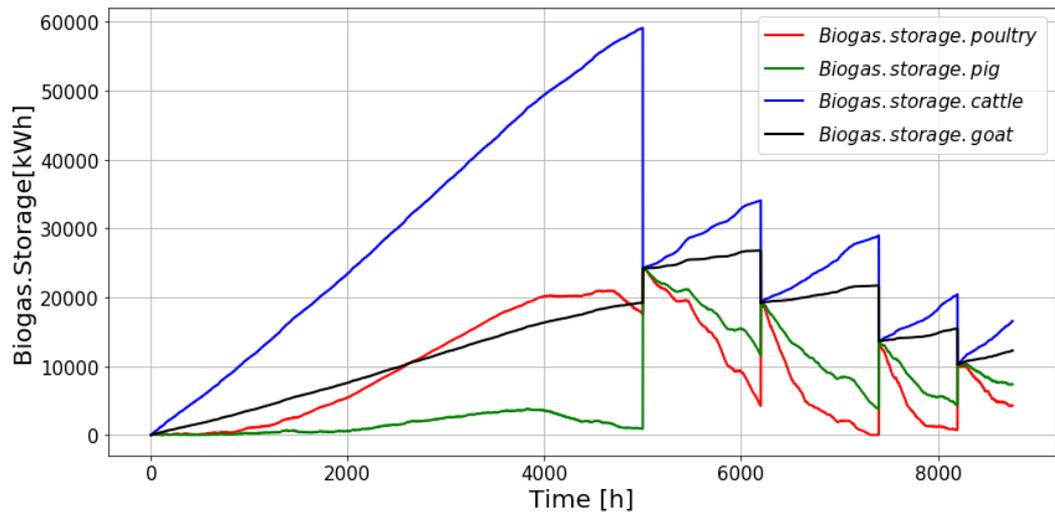


Figure 9 – Evolution of the biogas storage of any animal with 4 exchange

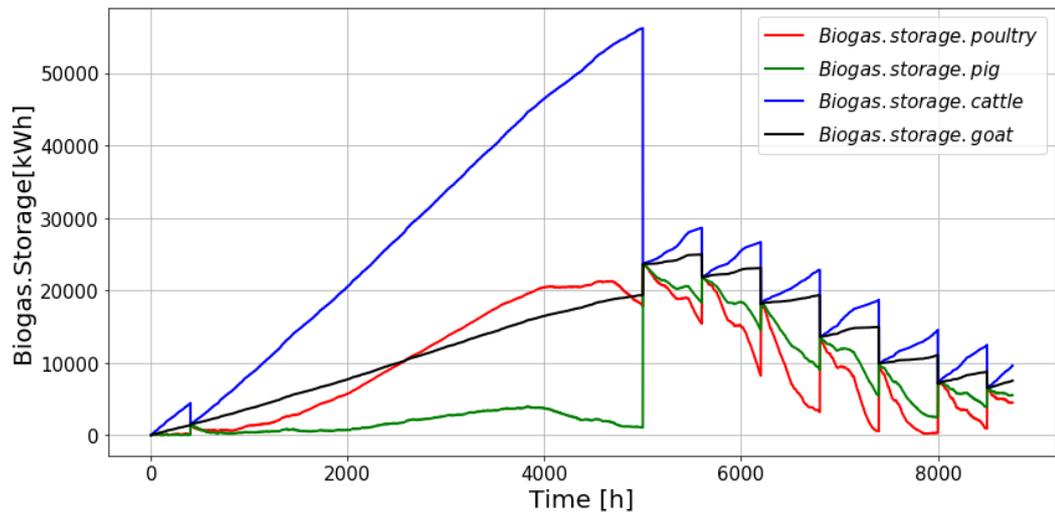


Figure 10 – Evolution of the biogas storage of any animal with 8 exchange

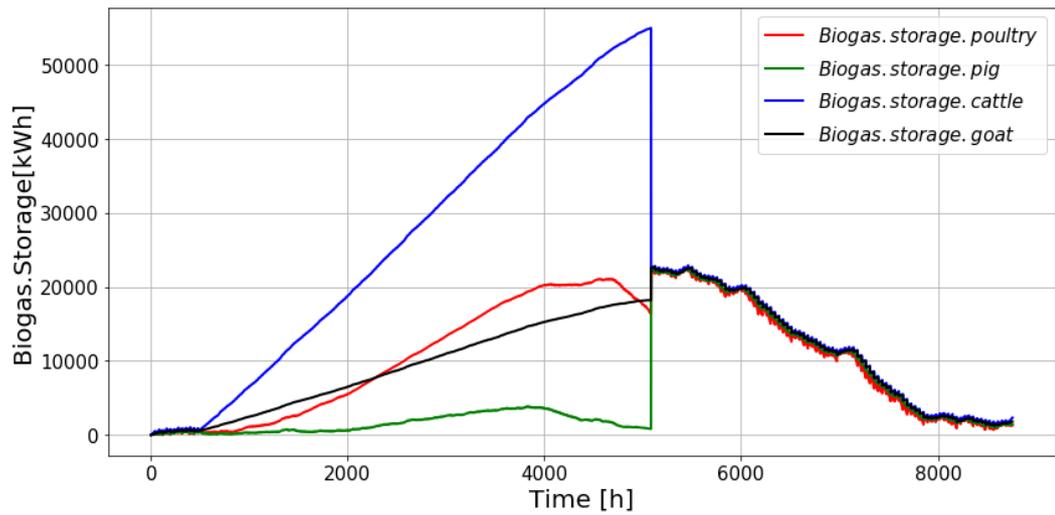


Figure 11 – Evolution of the biogas storage of any animal 100 exchange

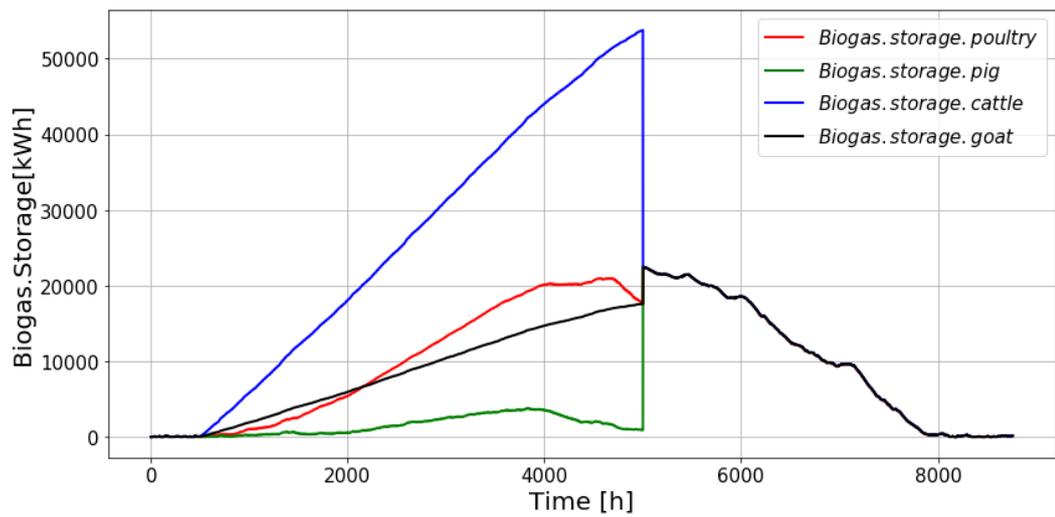


Figure 12 – Evolution of the biogas storage of any animal hour exchange