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Miscanthus for Combined Heat and Power: A Fuzzy Inference System

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Abstract In this paper the annual Combined Heat and Power (CHP) at a cogeneration's plant in relation to the cultivating area with miscanthus and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system). Data for this study were collected by research papers. This industrial unit will contribute to the local development as it can provide jobs for a great part of the rural population for the cultivation of miscanthus. The cultivation of miscanthus is one of the new promising energy crops for cogeneration and it constitutes a way out from the problems that the agricultural sector faces nowadays. In this paper an ideal solution was estimated which is formulated as follows "the cogeneration's plant absorbing the miscanthus's production of a cultivating area of 2,838 acres and having a mean land's yield in the order of 7.6 tons dm/acre/year would produce 10,000 KW of cogeneration annually". 21,568 tons dm of miscanthus annually should be consumed (burnt) for the operation of a cogeneration plant of 10 MW (10,000 KWh) which will cover the electricity's needs of 3,530 households as well as the demand for space heating and hot water (district heating) of 647 dwellings. 2,838 acres cultivated with miscanthus are required for the production of this amount of dry biomass. Such an area of land would offer a complementary occupation to a significant number of young farmers for the cultivation of miscanthus which will probably be well subsidized, will provide economic motives to the planters, support the agricultural economy and sustain the population in the countryside.

Keywords miscanthus, cogeneration's plant, fuzzy logic, Mamdani-type FIS

Introduction

The authors believe that the establishment of a cogeneration's industrial unit which will use miscanthus as a plant raw material will comprise respiration on local level because apart from the simultaneous production of electrical power and heat in a single process, the cultivation of miscanthus which will probably be well subsidized, will provide economic motives to the planters, support the agricultural economy and sustain the population in the countryside. In this paper the annual Combined Heat and Power (CHP) at a cogeneration's plant in relation to the cultivating area with miscanthus and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system).

Miscanthus (*Miscanthus giganteus)*

This grass is a C4, triploid hybrid of uncertain origin, which was probably the result of a cross between *Miscanthus sinensis* and *M. sacchariflorus.* It has a vigorous rhizomatous system from which a dense root mat develops to a depth of 0.4 m with some to 2.5 m. Its pith-filled canes grow to a height of 4 m. It shows a good combination of high light, water and nitrogen use efficiencies, but will not tolerate stagnant water or prolonged periods of drought [1].

Rhizomes or micropropagated plantlets are used to establish the crop, which means that this cost is relatively high (7% of crop production) [2]. An herbicide application may be needed in spring after planting but after that the fall of leaf litter in the winter should suppress weeds. The addition of N has some benefit but no increase in yield was seen above 150 kg N/ha/y [1]. It has an annual cropping cycle with a productive cropping period of 20 years. Full productivity is reached three years after establishment [2]. Harvest takes place from November to February [3].

Trials in Europe from Sweden to Portugal have been taking place since the mid 1990's using many different genotypes and 22-30 t dm/ha/y is achievable from central Germany to southern Italy though the latter needed irrigation (Lewandowski, 1998). Irrigation may be a requirement under southern European growing conditions where it represents 13% of total cost of production [2]. The miscanthus's yield for the infertile rainfed lands ranges from 3.2-7.2 tons dm/acre/year, while for the fertile irrigated lands from 8.8-12 tons dm/acre/year [1-4]. An annual gross energy yield of 19.6 Mj/kg of dry matter has been calculated [5]. This grass represents one of the more developed crops for biomass production. There is a range of varieties available covering most of the climatic conditions in Europe and it appears that it will continue to be developed for this type of production. Other benefits include its low nutrient and water requirements though irrigation seems to be important in southern Europe and there are no reports of plant diseases limiting its production [1]. Its establishment, cultivation and harvesting can all be achieved with conventional methods and equipment. Other possible uses for this grass include specialised paper production and animal bedding, as it is very absorbent.

Cogeneration or Combined Heat and Power (CHP)

Cogeneration or Combined Heat and Power (CHP) is defined as the simultaneous production of electrical power and heat in a single process. It is based on the simple principle that, in a plant dedicated to electricity production alone, only a portion of the primary energy of fuel is actually converted into electrical power, ranging typically from 35% to 40%. The remaining part is lost in the form of heat dissipated to the environment. The traditional power stations do not use the heat by-product and there are other losses due to transmission of electricity to homes over long distances [6].

Cogeneration allows increasing the conversion efficiency of the primary energy of fuel by means of heat recovery for industrial or civil uses. In other terms, cogeneration grants a significant energy saving in comparison with separate production of electricity (in a traditional power station) and heat (in a traditional heat station). Cogeneration has a very high energy utilization efficiency that can reach 85%, while the separate production of electricity and heat has a efficiency of 58% [7] (Fig. 1).

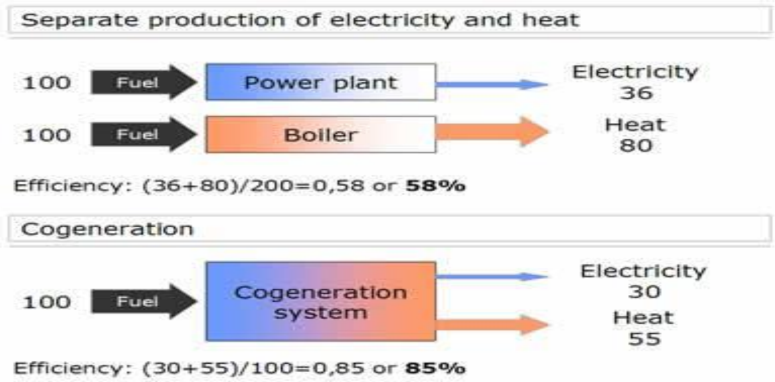

Figure 1: Efficiency of Cogeneration and Separate production of electricity and heat

Biomass-fired CHP systems can provide heat or steam for use in industry (e.g. the pulp and paper, steel, or processing industries) or for use for space and water heating in buildings, directly or through a district heating network in a maximum distance of 1500 meters.

A typical CHP system provides [6]:

a) Distributed generation of electrical and/or mechanical power.

b) Waste-heat recovery for heating, cooling, or process applications. CHP systems consist of a number of individual components - prime mover (engine), electricity generator, heat recovery, and electrical interconnection. The type of equipment that drives the overall system (i.e., the prime mover) typically identifies the CHP unit.Prime movers for CHP units include reciprocating engines, combustion or gas turbines, steam turbines, microturbines, and fuel cells. These prime movers are capable of burning a variety of fuels, including natural gas, coal, oil, biomass to produce shaft power or mechanical energy (EPA, 2007).

A biomass-fueled Combined Heat and Power installation is an integrated power system comprised of three major components [8]:

1. Biomass receiving and feedstock preparation.
2. Energy conversion - Conversion of the biomass into steam for direct combustion systems or into biogas for the gasification systems.
3. Power and heat production - Conversion of the steam or syngas or biogas into electric power and process steam or hot water.

The lowest cost forms of biomass for generating electricity are residues. Residues are the organic byproducts of food, fiber, and forest production, such as sawdust, rice husks, wheat straw, corn stalks, and sugarcane bagasse. Forest residues and wood wastes represent a large potential resource for energy production and include forest residues, forest thinnings, and primary mill residues. Energy crops are annual and perennial grasses and trees that are produced primarily to be used as feedstocks for energy generation, e.g. hybrid poplars, hybrid willows, switchgrass, etc.

The main obtainable benefits when a CHP unit works properly are [9]:

- Increased efficiency of energy conversion and use.
- Lower emissions to the environment of all the main greenhouse gases.
- In some cases, biomass fuels and some waste materials, such as refinery gases, process or agricultural waste, can be used. These substances can easily fuel a CHP plant and, if available directly in the place where the system works, may largely increase the cost-effectiveness, especially by reducing the costs for fuel supply and waste disposal.
- A real opportunity to develop more decentralized forms of power generation, where plants are designed to meet the needs of local consumers, providing high efficiency, avoiding transmission losses and increasing flexibility in system use.
- A real opportunity to increase the diversity in electricity generation and to provide competition in the power generation market.

Working with the Fuzzy Logic Toolbox

The Fuzzy Logic Toolbox provides apps to let you perform classical fuzzy system development and pattern recognition. In general, using the Fuzzy Logic Toolbox, you can [10-11]:

- Develop and analyze fuzzy inference systems
- Develop adaptive neurofuzzy inference systems
- Perform fuzzy clustering.

What Are Fuzzy Inference Systems?

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made or patterns discerned. The process of fuzzy inference involves: Membership Functions, Logical Operations and If-Then Rules. Two types of fuzzy inference systems can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined [12-14].

Mamdani-type inference is a type of fuzzy inference in which the fuzzy sets from the consequent of each rule are combined through the aggregation operator and the resulting fuzzy set is defuzzified to yield the output of the system.

Sugeno-type inference is a type of fuzzy inference in which the consequent of each rule is a linear combination of the inputs. The output is a weighted linear combination of the consequents.

Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. Mamdani's method was among the first control systems built using fuzzy set theory. It was proposed in 1975 by Ebrahim Mamdani [12] as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. Mamdani's effort was based on Lotfi Zadeh's 1973 paper on fuzzy algorithms for complex systems and decision processes [15].

Mamdani-type inference expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It is possible, and in many cases much more efficient, to use a single spike as the output membership function rather than a distributed fuzzy set. This type of output is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across the two-dimensional function to find the centroid, the weighted average of a few data points is used. In general, Sugeno-type systems can be used to model any inference system in which the output membership functions are either linear or constant [16-17].

Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems and computer vision. Because of their multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply (and ambiguously) fuzzy systems [18-19].

Methodology

Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools to build a Mamdani-type fuzzy inference system

The Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools were used in this paper to build a Mamdani-type fuzzy inference system (FIS). The following GUI tools were used to build, edit and view the fuzzy inference system:

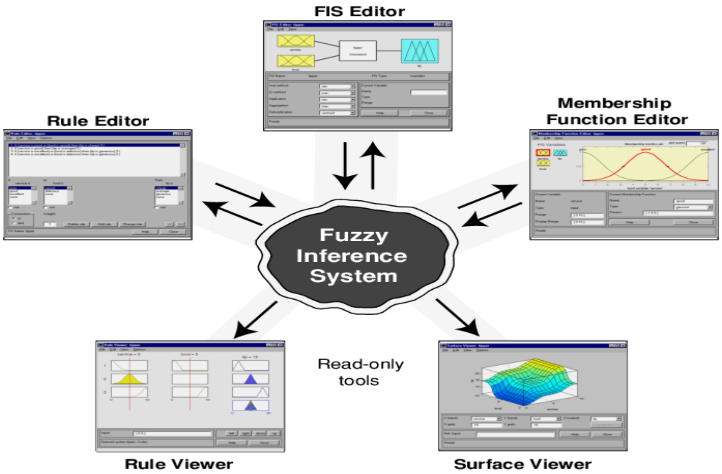

Figure 2: A Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools. The Membership Function Editor (top right), FIS Editor (center), Rule Editor (top left), Rule Viewer (bottom left) and Surface Viewer (bottom right).

Fuzzy Inference System (FIS) Editor to handle the high-level issues for the system—How many input and output variables? What are their names? Fuzzy Logic Toolbox software does not limit the number of inputs. However, the number of inputs may be limited by the available memory of the machine. If the number of inputs is too large or the number of membership functions is too big, then it may also be difficult to analyze the FIS using the other tools.

Membership Function Editor to define the shapes of all the membership functions associated with the input and output variables of the FIS.

Rule Editor to edit the list of rules that defines the behavior of the system using full English-like syntax.

Rule Viewer to view the fuzzy inference diagram. Rule Viewer is used as a diagnostic to see, for example, which rules are active or how individual membership function shapes influence the results. Rule Viewer lets you view the detailed behavior of a FIS to help diagnose the behavior of specific rules or study the effect of changing input variables.

Surface Viewer to view the dependency of one of the outputs on any one or two of the inputs. It generates and plots an output surface map for the system. Surface Viewer generates a 3-D surface from two input variables and the output variable of a FIS.

The Problem

Given two sets of numbers, the first one between 0 and 3,700 acres and the second one between 0 and 12 tons dm/acre/year that respectively represent the cultivating area with miscanthus and the land's yield. What should the annual cogeneration be? In this paper the annual Combined Heat and Power (CHP) at a cogeneration plant in relation to the cultivating area with miscanthus and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system). Data for this study were collected by research papers concerning the range of miscanthus yield for various land categories (infertile rainfed land, fertile irrigated land).

Results & Discussion

Building of a Mamdani-type Fuzzy Inference System

Fuzzy Approach

The following 3 rules were set:

- If cultivating area with miscanthus is small and land is infertile rainfed, then the annual cogeneration is low;
- If cultivating area with miscanthus is satisfactory, then the annual cogeneration is satisfactory;
- If cultivating area with miscanthus is large or land is fertile irrigated, then the annual cogeneration is high.

The four basic steps for building and simulating of a fuzzy logic system are the following [11, 17, 20]:

- Defining inputs and outputs;
- Creating membership functions;
- Creating rules;
- Simulating the results of a fuzzy logic system.

1st Step-defining Inputs and Outputs

The Mamdani-type fuzzy inference system was selected in the FIS Editor. This problem has 2 input variables and 1 output variable. The input 1 variable is the "cultivating area with miscanthus". The input 2 variable is the "land's yield". The output variable is the "annual cogeneration" (Fig. 3).

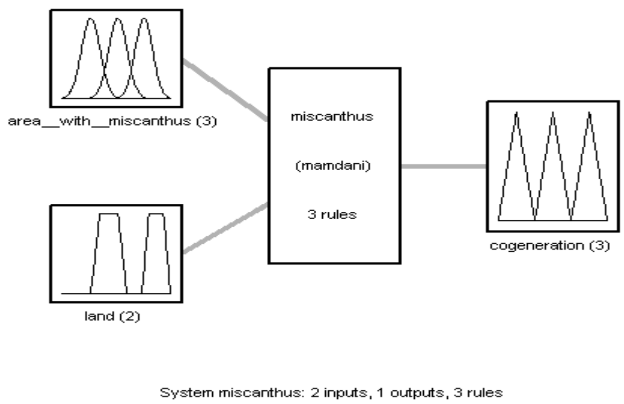

Figure 3: Defining inputs and outputs

2nd Step-creating Membership Functions

The membership functions for the 3 variables were defined, namely for the variables: "cultivating area with miscanthus", "land's yield", "annual cogeneration". The gaussmf was selected as a type of membership function for the input 1 variable "cultivating area with miscanthus". The number of membership functions is 3 (small, satisfactory, large). The range of "cultivating area with miscanthus" is between 0 and 3,700 acres (Fig. 4).

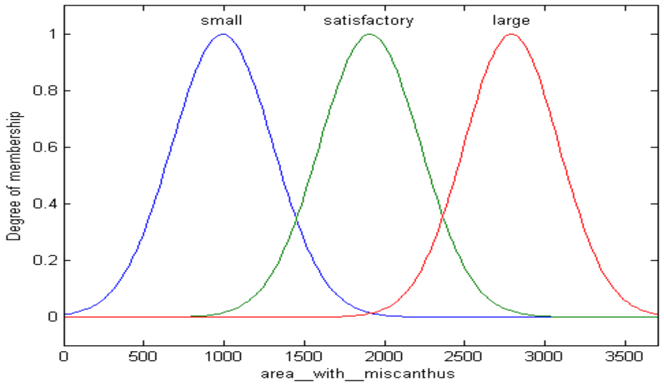

Figure 4: The three membership functions (small, satisfactory, large) for the input 1 variable "cultivating area with miscanthus"

The trapmf (trapezoid membership function) was selected as a type of membership function for the input 2 variable "land's yield". The number of membership functions is 2 (infertile rainfed, fertile irrigated). The range of "land's yield" is between 0 and 12 tons dm/acre/year (Fig. 5).

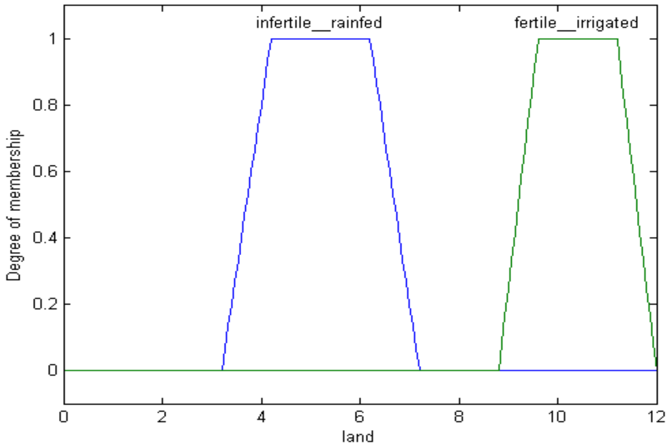

Figure 5: The two membership functions (infertile rainfed, fertile irrigated) for the input 2 variable "land's yield"

The trimf (triangular membership function) was selected as a type of membership function for the output variable "annual cogeneration". The number of membership functions is 3 (low, satisfactory, high). The range of "annual cogeneration" is between 0 and 12,150 KW of cogeneration (Fig. 6).

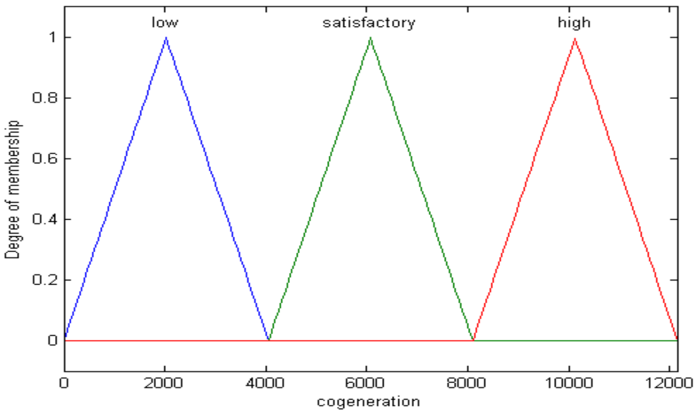

Figure 6: The three membership functions (low, satisfactory, high) for the output variable "annual cogeneration"

3rd Step-creating Rules

Rule statements are constructed automatically in the Rule Editor. The 3 rules of fuzzy approach were added in the Rule Editor (Fig. 7).

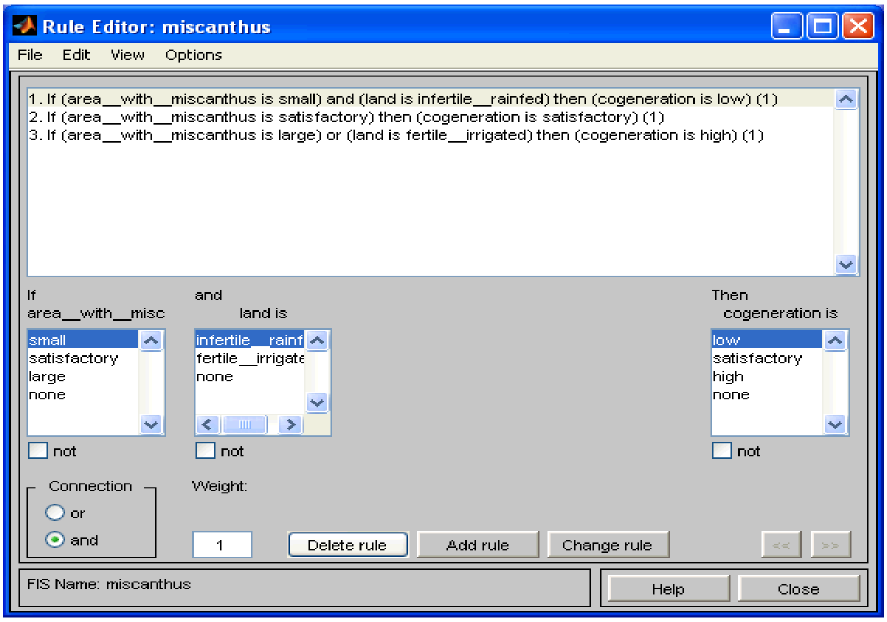

Figure 7: The rule editor: the three rules are appeared in the up part of this window

4th Step-simulating the Results of a Fuzzy Logic System

The results of Rule Viewer (Fig. 8) and Surface Viewer (Fig. 9) of a Mamdani-type fuzzy inference system are simulated and analyzed.

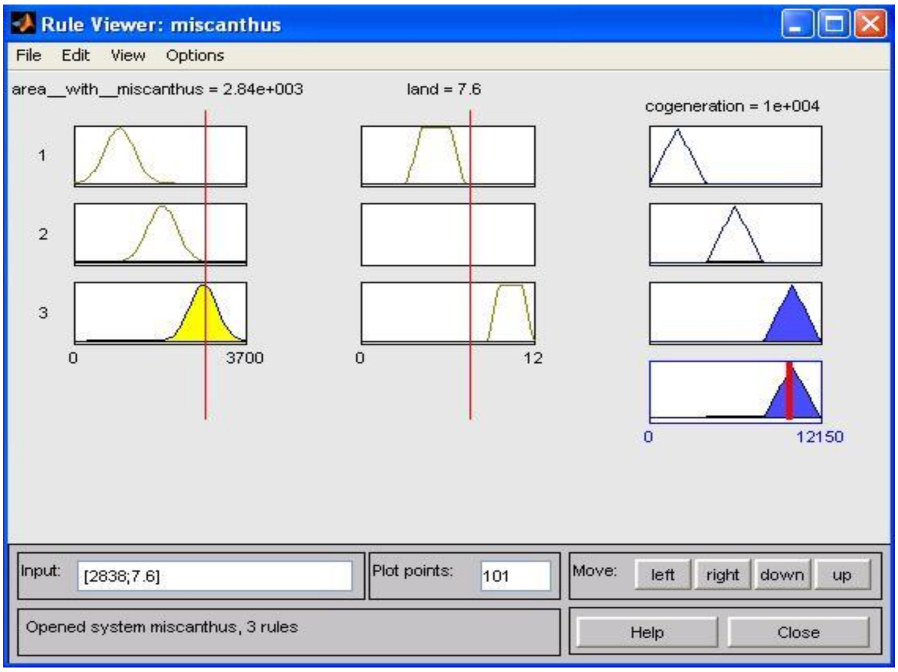

Figure 8: The rule viewer

In the Rule Viewer (Fig. 8), each column shows a set of membership functions for a particular variable. 3 membership functions for “cultivating area with miscanthus” input 1 variable, 2 membership functions for “land’s yield” input 2 variable and 3 membership functions for “annual cogeneration” output variable are presented in Fig. 8.

Each membership function in this set is associated with a particular rule and maps input variable values “cultivating area with miscanthus” and “land’s yield” to rule input values. In other words, the number of rows here is the number of rules that the authors have. The first row corresponds to the first rule, the second row corresponds to the second rule and the third row corresponds to the third rule. The plots in the output column show how the rules are applied to the output variable. The bottom right plot shows how the output of each rule is combined to make an aggregated output and a defuzzified value. The red line provides the defuzzified value for the annual cogeneration. The input value for "cultivating area with miscanthus" is 2,838 acres and the input value for "land's yield" is 7.6 tons dm/acre/year and they correspond to an output value for "annual cogeneration" equal to 10,000 KW of cogeneration.

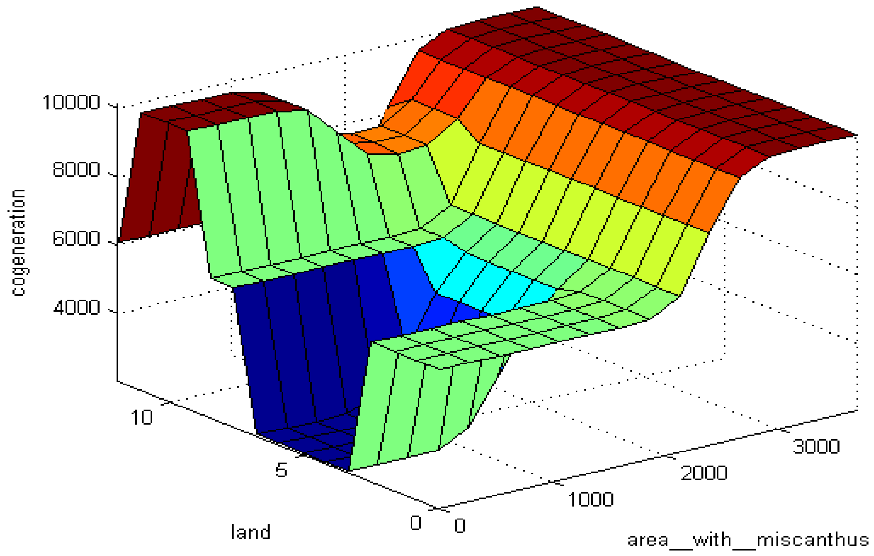

Figure 9: The surface viewer: annual cogeneration as it is affected by the cultivating area with miscanthus and land's yield

The Surface Viewer (Fig. 9) displays a surface that represents a mapping from the "cultivating area with miscanthus" and the "land's yield" to the "annual cogeneration". This shows a high value of annual cogeneration for large cultivating area with miscanthus and fertile irrigated lands, a low value of annual cogeneration for a small cultivating area with miscanthus and infertile rainfed lands as well as a large flat area in the middle corresponding to a satisfactory (medium) annual cogeneration for satisfactory (medium) cultivating area with miscanthus.

Cogeneration plant 10 MW fuelled with miscanthus for the simultaneous production of heat and electricity

21,568 tons dm of miscanthus annually should be consumed (burnt) for the operation of a cogeneration plant of 10 MW (10,000 KWh) which will cover the electricity needs of 3,530 households as well as the demand for space heating and hot water (district heating) of 647 dwellings. 2,838 acres cultivated with miscanthus are required for the production of this amount of dry biomass. 7.6 tons dm / acre / year were taken as a mean yield of miscanthus. According to EPA (2007) 10 KW / residence are required for district heating.

2,462 Kg / hr (consumption, combustion of miscanthus dry matter) x 4,110 Kcal / Kg (calorific value of miscanthus) = 10,116,079 Kcal / hr or 11,765,000 Wh (11,765 KWh).

11,765,000 Wh corresponding to 100% (total amount of biomass burnt)

X =? cogeneration represents 85% (efficiency)

The Combined Heat and Power (CHP) is with approximation X = 10,000 KWh of which 3,530 KWh of electricity (30% efficiency) and 6,470 KWh of heat (55% efficiency), while the energy losses amount to 1,765 KWh (15% efficiency).

10,000 KWh of cogeneration corresponding to 0.85 (85% efficiency)

X =? electricity corresponds to 0.30 (30% efficiency)

The electricity's production is X = 3,530 KWh of electricity.

10,000 KWh of cogeneration corresponding to 0.85 (85% efficiency)

X =? heat corresponds to 0.55 (55% efficiency)
The heat's production is X = 6,470 KWh of heat.
10,000 KWh of cogeneration corresponding to 0.85 (85% efficiency)
X =? energy losses corresponding to 0.15 (15% efficiency)
The energy losses amount to X = 1,765 KWh.
During the summer the hot water produced in a cogeneration plant could be used for drying of agricultural products or more generally in agricultural plants or wood-based industries to meet their heating needs.

Conclusion

Fuzzy inference is a method that interprets the values in the input vector and based on user-defined rules, assigns values to the output vector. Using the editors and viewers in the Fuzzy Logic Toolbox, the rules set were built, the membership functions were defined and the behavior of the fuzzy inference system (FIS) was analyzed. In this paper the annual Combined Heat and Power (CHP) at a cogeneration's plant in relation to the cultivating area with miscanthus and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system). Data for this study were collected by research papers concerning the range of miscanthus yield for various land categories (infertile rainfed land, fertile irrigated land). This industrial unit will contribute to the local development as it can provide jobs for a great part of the rural population for the cultivation of miscanthus. The cultivation of miscanthus is one of the new promising energy crops for cogeneration and it constitutes a way out from the problems that the agricultural sector faces nowadays. The authors built a Mamdani-type fuzzy inference system, namely defined inputs and outputs, created membership functions, created rules and the authors simulated the results of Rule Viewer and Surface Viewer of the fuzzy inference system. The Surface Viewer shows a high value of annual cogeneration for large cultivating area with miscanthus and fertile irrigated lands and a satisfactory (medium) annual cogeneration for satisfactory (medium) cultivating area with miscanthus. By the Rule Viewer is shown that the input value for "cultivating area with miscanthus" is 2,838 acres and the input value for "land's yield" is 7.6 tons dm/acre/year and they correspond to an output value for "annual cogeneration" equal to 10,000 KW of cogeneration. This constitutes the ideal solution in the problem, which was found by using of the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab. In other words, the cogeneration's plant absorbing the miscanthus's production of a cultivating area of 2,838 acres and having a mean land's yield in the order of 7.6 tons dm/acre/year would produce 10,000 KW of cogeneration annually. 21,568 tons dm of miscanthus annually should be consumed (burnt) for the operation of a cogeneration plant of 10 MW (10,000 KWh) which will cover the electricity's needs of 3,530 households as well as the demand for space heating and hot water (district heating) of 647 dwellings. 2,838 acres cultivated with miscanthus are required for the production of this amount of dry biomass. Such an area of land would offer a collateral occupation to a significant number of young farmers for the cultivation of miscanthus which will probably be well subsidized, will provide economic motives to the planters, support the agricultural economy and sustain the population in the countryside.

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