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Research paper

# Biomass sorghum production risk assessment analysis: A case study on electricity production in the Po Valley

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ABSTRACT

The risk associated to the production of biomass sorghum (*Sorghum bicolor* (L.) Moench) to feed a power plant in the Po Valley (Italy) was studied with a modelling approach. Available biomass was modelled by CropSyst, coupled to a "sorghum haying model", using three sorghum genotypes, of contrasting earliness (early, medium-late and late), on a mosaic of virtual farms created in the target cropping area. The energy performance, from cradle to farm gate, of the biomass production system was performed calculating Energy Return on Investment (EROI), Net Energy Gain (NEG) and Energy Use Efficiency (EUE).

The highest baled biomass (14.0 Mg DM $ha^{-1}y^{-1}$) was obtained with the early maturity type that had less haymaking failures (6.9%), followed by the late and medium-late genotypes. As a consequence, the early maturity type had the highest probability of exceeding the biomass needs of the power plant on a cropping area of 4222 ha. The early genotype also had the highest EROI (14.8) and NEG (205.6 GJ $ha^{-1}y^{-1}$) and the lowest EUE (1.06 GJ $Mg^{-1}$ DM $y^{-1}$).

To achieve a 0.5 probability to exceed the target biomass production, the area to be cultivated should be 4558, 5160 and 4962 ha for the early, medium-late and late genotypes, respectively.



## 1. Introduction

As indicated in the Renewable Energy Directive [1] Europe considers the Renewable Energy Sources (RES) able to reduce fossil energy consumptions and greenhouse gas (GHG) emissions [2]. In this frame, biomass is considered an important source of bioenergy [3], biomaterials and chemicals [4] and is also a promising and interesting energy source to mitigate greenhouse gas emissions [5,6]. However, biomass production for energy purposes also has some implications and risks that can negatively affect the sustainability of the entire bioenergy system [7].

In order to identify the potential constraints involved in a bioenergy production system, the development of a risk assessment analysis is necessary to provide a practical management tool for policy makers, planners and the bioenergy industries and thus support policy development and bioenergy deployment at different scales [8].

Risk assessment analysis involves various disciplines such as engineering methodologies, ecology, physics, psychology, statistics, sociology, chemistry, economics and toxicology. In scientific literature there are some studies regarding the risk assessment analysis on climate change impact on crop yields [9–11], on pesticides seeping into surface water [12], on the use of genetically modified organisms (GMO) into the environment [13], and on the evaluation of bioenergy systems sustainability [8].

In this study a production risk assessment analysis was performed to explore the main constrains related to the cultivation of biomass sorghum (*Sorghum bicolor* (L.) Moench) and identify management options to feed a power plant in the Po Valley (northwestern Italy) with sorghum biomass. Sorghum is a low input [14,15] drought tolerant [16] annual C4 herbaceous crop that can be used as a dedicated ligno-cellulosic energy crop in energy production [17,18], namely anaerobic digestion, second generation bioethanol production [14,19,20] and to generate electricity by direct combustion [19].

The use of sorghum for bioenergy purposes (i.e. to generate electricity by direct combustion) should take into consideration two aspects: (i) the choice of the correct genotype and (ii) the use of suitable harvest technology; the combination of these two factors is essential to optimize the post-harvest field drying process [19,21–23]. In a modelling study to compare three sorghum maturity type of contrasting earliness [24] it was seen that the best

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trade-off between biomass production and biomass moisture content at the time of baling was achieved with the earliest genotype. In addition an early maturity type, having a shorter field drying period, is less at risk of being exposed to adverse weather conditions. For this reason to reduce the risk of crop failure and to guarantee the coverage of biomass power plant needs, the use of an early sorghum genotype is preferable; yet on the other hand, a late genotype is likely to yield a higher biomass production [21] even if the risk of crop failure is higher than an early and a medium-late genotype.

Rendering a large quantity of baled biomass available for combustion at the power plant is essential for obtaining a positive energy balance and an economically profitable production [25].

Identification of the energy inputs and outputs involved in a bioenergy system is fundamental to quantify the sustainability of the entire biomass supply chain, as reported by Arodudu et al. [26], who suggested using energy-based indices as measures of bioenergy system performance.

A simplified energy balance, from cradle to farm gate [27] was carried out in this study to quantify the energy input and output involved in the biomass sorghum supply chain and to calculate three energy bases indexes; Energy Return on Investment (EROI) defined as the ratio between the amount of energy produced (expected return) and the non-renewable primary energy needed to produce it (investment) [28], Net Energy Gain (NEG) defined as the gained difference in energy between the gross energy output produced (i.e. the energy content of the biomass at the farm gate) by the bioenergy system and the total energy invested to obtain it (i.e. the fossil energy input) [29] and Energy Use Efficiency (EUE) defined as the energy requirement to produce a certain quantity of dry matter [30].

The main purpose of this work was to carry out a production risk assessment analysis with the following objectives: (1) To estimate the sorghum production area needed to satisfy 70% (or 64000 Mg DM $y^{-1}$) of the needs of a biomass power plant in the Po Valley; and (2) to compare the biomass production and energetic performance of three sorghum genotypes with different earliness (early, medium-late and late) in order to determine the probability of different genotypes to exceed 70% (or 64000 Mg DM $y^{-1}$) of the power plant needs.

## 2. Materials and methods

### 2.1. Description of the case study

This work was commissioned by the Lombardy Region as part of a feasibility study to convert a sugar factory, that was closed in accordance to the 2006 European Reform of sugar Common Market Organization [31], to a biomass power plant. Farmer associations in agreement with the Lombardy Region imposed the constraint that the power plant should operate on feedstock produced or recovered on farm, within the ex-sugar factory supply area. In particular it was agreed that 70% of power plant needs would be covered by dedicated biomass sorghum cultivations.

It was calculated that to satisfy 70% of the needs of the power plant, characterized by a thermal capacity of 15 $MW_{el}$ (50 $MW_{th}$), 64000 Mg DM $y^{-1}$of sorghum ($LHV_{dry}$ 15.7 MJ $kg^{-1}$) would be needed.

The study aimed at exploring the production risk and the energy performance of biomass sorghum cultivated to satisfy the above-mentioned power plant feedstock needs. Main objective of the study was the calculation of a reference cropping area to be planted annually with sorghum and the probability to exceed the power plant needs with the biomass baled on this cropping area. The energy performance was assessed calculating the Energy Return on Investment (EROI), Net Energy Gain (NEG) and the Energy Use Efficiency (EUE) along the whole production system with a cradle to farm gate approach.

### 2.2. Production risk assessment analysis

The production risk assessment analysis, whose structure is represented in Fig. 1, was performed according to the following list of actions:

1) Calculation of the target cropping area to be cultivated annually with sorghum, based on power plant needs and average biomass sorghum baled per hectare;
2) Creation of a mosaic of virtual farms, distributed in the biomass sorghum supply area, to support a long-term simulation (39 years) of biomass sorghum production;
3) Calculation of actual baled sorghum production in the biomass supply area using the CropSyst model [32] coupled to the “sorghum haying model” developed by Serra et al. [24], comparing three sorghum genotypes of contrasting earliness (early, medium-late and late);
4) Quantification of the probability of each sorghum genotype to exceed 70% (or 64000 Mg DM $y^{-1}$) of the total power plant needs, quantified using the data generated in a long-term (39 years) simulation on the mosaic of virtual farms.

**Action 1)** To calculate the target cropping area to be planted annually with sorghum, the amount of sorghum biomass needed to cover the power plant needs (64000 Mg $y^{-1}$) was divided by the average biomass production of a medium-late sorghum maturity type (Biomass 133 commercialized by Syngenta) tested in a multi-location experiment conducted in 2010 in the catchment area of the power plant as described by Serra et al. [24].

**Action 2)** To support long-term modelling of sorghum biomass production, a mosaic of virtual farms geo-referenced in the catchment area of the power plant was created in a three step process: a) determination of farm size; b) estimation of the proportion of land cultivated with sorghum on each farm; c) farm distribution in the catchment area of the power plant (Fig. 2).

a) Statistical information on farm size in the study area was obtained from ISTAT [33]. ISTAT data revealed an asymmetry in farm size distribution with a peak between 7 and 10 ha, and a wide range of frequency for larger farms (15 and 22 ha). To model a realistic distribution of farm sizes, a population of farms $i$ was modelled by sampling values from a gamma distribution with *shape* = *3* and *scale* = 0.125 and each farm was characterized by a total farm area $Fa_i$ (ha). The *shape* and *scale* of the parameters were chosen to generate sample values consistent with the distribution of ISTAT data. The farm shape arbitrarily assigned to the farms was a rectangle with a ratio $q$, randomly generated, between major and minor sides, $l_m$ and $l_n$:

$$q = \frac{l_m}{l_n}; 2 < q < 10 \quad (1)$$

b) The fraction $f_r$ of arable land in each farm to be cultivated with sorghum was derived from a survey carried out in 2010 with 20 farmers involved in the sorghum field trials [24]. Assuming that the maximum number of crops grown annually in a farm is three, the fraction $f_r$ of land dedicated to sorghum was set equal to 1/3.
c) It was assumed that the virtual farms were equally distributed around two focus centres: the biomass power plant (45°00′N,