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Energy production and carbon sequestration in wet areas of Emilia Romagna region, the role of Arundo Donax

Giulio Allesina[1*], Simone Pedrazzi[1], Fabrizio Ginaldi[2], Giovanni A. Cappelli[2], Marco Puglia[1], Nicolò Morselli[1], Paolo Tartarini[1]

[1] BEELab, University of Modena and Reggio Emilia, Department of Engineering "Enzo Ferrari", Via Vivarelli 10/1, Modena 41125, Italy
[2] Consiglio per la Ricerca in agricoltura e l'analisi dell'Economia Agraria (CREA), Via di Corticella 133, Bologna 40128, Italy.

Corresponding Author Email: giulio.allesina@unimore.it

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ABSTRACT

This work investigated the utilization of giant reed as energy crop applied marginal areas of the municipality cluster "Unione Terre d'Argine" (UTA), Northern Italy. On one hand, the researchers modeled the giant reed productivity in terms of ton/year for each town of the cluster. They focused on those areas neighboring the local rivers and channels kept unused for farming activities: i.e. riverbanks or detention basin shores. On the other hand, experimental tests were performed to determine the behavior of giant reed as fuel in pilot-scale gasification power plants. Results showed the high potential of small or pilot-scale gasifiers to increase the sustainability of river maintenance operations. From its gasification it is possible to produce electrical power together with biochar. Biochar is a powerful soil amendment that can be used straight in the riverbanks. The tandem process between giant reed growth and its gasification leads to 150 kg of CO_2 sequestered for every ton of giant reed processed. Furthermore, the energy production from waste biomasses will help to perform better and more regular maintenance operation to the local rivers and channels, thus reducing the negative effects of possible floods.

1. INTRODUCTION

River maintenance activities are heavy operation required in order to reduce the risk of floods and to preserve the environment of rivers and lakes [1-3]. Poor maintenance or no maintenance of the river banks result in a decrease of the water flow cross width and in an increase of the river internal roughness, thus reducing the water speed and increasing the water level [2].

However, riverbanks are a fertile environment ideal for several plants species. Its peculiar conditions lead to a fast and constant growth of the vegetation, requiring frequent maintenance to mitigate flood risk [2]. In Italy, one of the most abundant species that growth in the aquatic wet areas is giant reed (*Arundo Donax*) [4].

Giant reed is an invasive C3 perennial specie suitable as energy crop. In-fact, giant reed is a biomass with high biochemical methane potential excellent for anaerobic digestion [5-6]. Giant reed is already used as fuel for electric and thermal energy production via combustion, pyrolysis and gasification [7-8].

Giant reed has a great tolerance to different types of soils [9], high biomass productivity with low agronomic inputs [10] and the obtainable energy per hectare is higher than the energy achievable from traditional crops [11]. Arundo Donax crop has a high potential for phytoremediation as results of a very deep root system that enhance soil aggregation, nitrates and other pollutants absorption [12]. Giant reed is therefore emerging as a promising solution for the recovery of less productive soils and the preservation of fragile ecosystems, such as marginal areas around the riverbeds [4].

However, the conversion of Arundo Donax into energy is not immediate. In-fact, fresh cut moisture content (over 50%), a not negligible ash content (4-6%) and leaf presence are some factors that force to adopt several pre-treatment such as chipping, sieving and drying in order to use this biomass as fuel for bio-energy power plant [12-13].

This paper investigates the use of Arundo donax as fuel for small-scale gasifiers installed in wet areas of the Emilia Romagna Region (North of Italy). In particular, the marginal wet areas of the municipality cluster Unione Terre d'Argine (UTA) are here considered. UTA towns are: Campogalliano, Carpi, Soliera and Novi di Modena. In these areas, the Secchia river flows and there is a net of irrigation and drain canals where giant reeds can growth for energy and for phytoremediation purposes.

First, a giant reeds productivity assessment via spatially explicit crop models was done considering the marginal areas of the municipalities union. Second, chipped giant reeds were tested as fuel in an All Power Labs PP20 gasifier [14] in order to assess technical feasibility of this particular fuel. Finally, a prevision concerning the annual electrical energy and CO_2 sequestration obtainable from the gasification of giant reeds crop applied to these marginal areas was reported.

2. MATERIALS AND METHODS

2.1 Simulation of Arundo Donax crop productivity

The BioMA framework [15], currently in use at the Joint Research Centre of the European Commission for yield forecasting [14], was used as modelling solution (MS).

BioMA is a platform to run biophysical models on generic spatial units. In this realization, the Arundo MS runs simulations at daily time step and includes four main stateless components also depicted in Figure 1:

- crop component for the simulation of the giant reed development and growth [16];
- weather provider which makes available weather data to the MS;
- soil component which reproduces the water redistribution across the soil layers according to a cascading (tipping-bucket) method [18];
- agro-management component, which triggers the occurrence of agricultural operations at run time, according to set of rules based on management decisions and/or states of the system [19].

The MS manages the simulation time and the call order of the simulation components within a time step, so that different simulation components can be run synchronously.

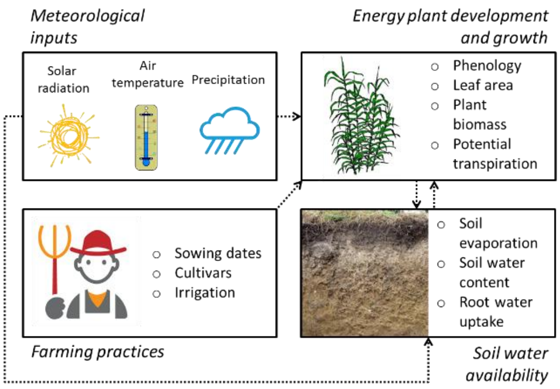

Figure 1. Diagram of the modelling solution targeting the simulation of giant reed in the study area (adapted from [3])

A satellite image of the UTA district is depicted in Figure 2. Yellow lines are cities borders. The southern city is Campogalliano, the northern is Novi di Modena and in the middle there are Carpi (west side) and Soliera (east side). Marginal areas, highlighted in light blue, are the Secchia riverbanks, artificial lakes, detention basins, drainage ditches and irrigation canals. Marginal zones were mapped and georeferenced via GIS software, defining attributes such as geographic coordinates, polygon areas (m^2) and perimeters (m).

Daily downscaled weather data (25 km^2 spatial resolution) for baseline (1991-2010) were extrapolated from the MODEXTREME database [20]. Weather data were corrected using the E-OBS gridded observational dataset for precipitation and surface temperature [21]. The MS was adjusted according to Stella et al. [17], who calibrated the model using field observations on stems dry, leaf area index and leaves.

For each polygon, seasonal total aboveground (ABG), biomass [ton/ha] were calculated and then multiplied by the related area to compute the total dry mass ABG_{tot} [ton_{dry}] that can be achieved by each marginal area. The total seasonal biomass productivity in the marginal zones of the UTA district were calculated summing up the partial results from each area.

Figure 2. Detail of the simulated study area (UTA district)

2.2 Gasification tests

For a precise evaluation of the performance of Arundo Donax chips as fuel, a 20 kW_{el} gasifier-engine pilot plant was used. The model chosen for the experimental tests is the PP20 Power Pallet depicted in Figure 3, manufactured by the company ALL Power Labs [14]. The system consists in fuel hopper of about 0.33 m^3 of volume, an auger biomass moving system from the hopper to the reactor, a single throat downdraft fixed bed gasifier provided with a filtration stage and an IC engine linked to a gen-head for electrical power production. General characteristics of this machine are listed in Table 1. The machine produces also biochar: a carbonaceous by-product with high porosity and suitable as soil admentant [4].

The system is designed to operate with a wide selection of biomasses, i.e. wood chips, corn cobs and walnut shells. Despite the fuel flexibility, Arundo Donax is not listed in the suitable or acceptable feedstocks. For this reason coupled with bridging issues described in the result section, a mixture of 50% Arundo Donax 50% fir wood chips w/w was used. A sample of chipped giant reeds is illustrated in Figure 4.

Table 1. All Power Labs PP20 characteristics [14]

Characteristic	Value
Continuous electrical power rating	15 kW_{el} @ 50 Hz
Continuous thermal power rating	20 kW_{th} at 15 kW_{el}
Biomass P16 W10 consumption	1.2 kg/ kW_{el}
Biomass moisture content	5-30%wt.
Biochar production	0.5-5%wt. of inlet biomass
Overall electrical efficiency with P16 W10	18.5 %

Figure 3. All Power Lab PP20 gasifier [14]

Figure 4. Chipped giant reed sample

The dry biomass consumption was evaluated starting from the as-received value as described by the following equation:

$$m_{bio,dry} = m_{bio,ar}(1 - M) \tag{1}$$

where $m_{bio,dry}$ [kg] is the dry biomass consumption, $m_{bio,ar}$ [kg] is the as-received biomass consumption and M is the moisture content. The specific consumption is defined by the following equation:

$$c = \frac{m_{bio,dry}}{E_{el,tot}} \tag{2}$$

where $E_{el,tot}$ [kWh] is the total electrical energy produced during the test. The overall electrical efficiency is evaluated as:

$$\eta_{tot,el} = \frac{E_{el,tot}}{m_{bio,dry} HHV_{bio,dry}} \tag{3}$$

where $HHV_{bio,dry}$ [MJ/kg] is evaluated using the biomass elemental analysis and the following formula suggested by Channiwala [22]:

$$HHV_{dry} = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1ASH \tag{4}$$

where C, H, N, S, O [%wt.] are the weight fractions of the respective elements, ASH [%wt.] is the ash content in the dry sample. Table 2 resumes the elemental composition of the Arundo Donax and fir wood chips samples obtained with an EA 1100 CHNS-O elemental analyzer. The ash amounts were measured through a 4 hours muffle furnace calcination [23]. Gasification tests were performed with air-dried biomass with an average moisture of 16%.

Finally, the Tar Sampling Procedure [24] was applied to calculate tar and particulate amount in the syngas in front of the engine manifold. This analysis investigates the quality of the gas in terms of pollutant content and indicates if the syngas is acceptable or not for long term IC engines running.

Table 2. Arundo Donax and fir wood chips elemental compositions and HHVs

Element	Arundo Donax	Fir
Carbon C [%wt.]	40.63	45.36
Hydrogen H [%wt.]	5.30	6.51
Nitrogen N [%wt.]	1.10	0.51
Sulphur S [%wt.]	0	0
Oxygen O [%wt.]	40.69	47.12
ASH [%wt.]	12.28	0.5
HHV_{dry} [MJ/kg]	15.66	18.61
$HHV_{dry,mix,50-50}$ [MJ/kg]	17.13	

3. RESULTS

3.1 Arundo Donax crop productivity

Arundo Doxax seasonal productivity in the marginal zones of each town of the UTA district is reported in Table 3. The marginal zones have a total area of about 477 ha. The town with the higher marginal zones area is Novi di Modena (142.71 ha), instead the town with the smaller marginal area is Soliera (76.40 ha). The average AGB value for the UTA district is 54.22 ton/ha, the total AGB is 26 thousands tons. The higher AGB value was obtained for the marginal zones of Novi di Modena (55.10 ton_{dry}/ha). In general, Novi di Modena is the most suitable zones for Arundo Donax crop. In-fact, it has the higher value of marginal area and aboveground biomass seasonal productivity. However, crop productivity and ABG is very high compared to other energy crop like poplar which has an ABG of about 12 ton_{dry}/ha [5].

Table 3. Arundo Donax MS results

Town	Marginal area [ha]	ABG_{tot} [ton_{dry}]	ABG [ton_{dry}/ha]
Campogalliano	132.75	7065.82	53.23
Novi di Modena	142.71	7863.26	55.10
Carpi	125.46	6879.67	54.84
Soliera	76.40	4072.92	53.31
UTA district	**477.323**	**25881.67**	**54.22**

Figure 5. 20 years (2001-2020) total ABG in the UTA district

Figure 5 illustrates a map regarding the total AGB in the marginal areas of the UTA districts. The map is referred to a period of 20 years and it considers the weather condition of the 1991-2010 period taken from the MODEXTREME database [20].

The higher ABG values in deep green are obtained in the Secchia riverbanks (right of the map), in the 'Carpi Quinto' irrigation canal (center of the map) and in the Campogalliano artificial lakes (bottom of the map). The reason behind is that all these areas are characterized by a good water availability and soil condition for Arundo Donax growth.

3.2 Arundo Donax gasification tests

During the experimental campaign, some gasification tests with Arundo Donax only were done but they were unsuccessful because the auger was not able to push biomass on the top of the reactor. In-fact, the auger that moves the biomass from the hopper to the top of the gasification reactor is design to run with wood chips, walnut shells and corn cobs. Arundo Donax chips have an elongated shape with a low thickness as shown in Figure 4.

For this reason, the 50-50 mix was tested at nominal power load (15 kW), but the biomass feed velocity on the top of reactor was too low to balance the process. Then, a test at low power load (4.2 kW) was done and it was successful because the auger was able to supply the biomass regularly to the top of the reactor.

Test results are summarized in Table 4. The test length at steady state condition was about 2 hours at a power load of 4.2 kW, about 1/3 of the nominal power. A low power load affects the gasifier efficiency because the reactor is design to work properly at nominal load conditions. However, All Power Labs PP20 uses a single throat reactor architecture able to work with a high turn-down ratio value [25]. On her other hand, under this condition gasifier efficiency drops from 85% nominal value to 50% or lower. In addition, engine efficiency at partial load is lower respect to full load condition, i.e. engine with 30% of nominal efficiency at full load can reach 15% or lower at partial load [26].

All these aspects increase the specific consumption from 1.2 to 2.7 [kg_{dry}/kWh] and decrease the overall electrical efficiency from 18.5% to 7.72%. These unexpected results can be adjusted working on the Arundo Donax chipping together with a new auger design able to move faster the biomass from the hopper to the reactor.

Nevertheless, the gasification reaction of the 50-50 mix was acceptable as shown in Table 5 where syngas composition is summarized. The value in the table are in line with literature syngas composition of common air-blow fixed bed gasification [25].

Table 4. Gasification test results

Variable	Value
Generator power load [kW]	4.2
Test length [min]	124
Electrical energy produced $E_{el,tot}$ [kWh]	8.7
As received biomass consumption $m_{bio,ar}$ [kg]	28.20
Dry biomass consumption $m_{bio,dry}$ [kg]	23.68
Dry biomass specific consumption c [kg_{dry}/kWh]	2.72
Overall electrical efficiency $\eta_{tot,el}$ [%]	7.72

Regarding Tar Sampling results, the obtained value in front of the engine manifold are 210 mg/Nm^3 of tar and 53 mg/Nm^3 of particulate content. Tar number is slightly higher than literature suggested limit of 100 mg/Nm^3 [25], instead particulate number is very close to the limit of 50 mg/Nm^3 [25]. However, partial load running increases a lot the tar content in the syngas and decreases in parallel the gasifier efficiency. At nominal load condition, tar number may drop to values more in-line with literature.

Table 5. Gasification test syngas composition and HHV

Gas component	H_2	N_2	CO_2	CH_4	CO	HHV [MJ/Nm^3]
Value	20.1	39.5	11.6	1.5	14.3	5.98

3.3 Estimated energy production and CO_2 capture

From previous results, the seasonal Arundo Donax total ABG in marginal areas of the UTA district is 25881.67 tons. Considering a not optimized specific biomass consumption of 2.72 kg_{dry}/kWh, obtained in the experimental gasification tests, about 9515.32 MWh of electrical energy can be produced. This energy amount can balance the consumption of about 3172 families considering an annual family electrical energy consumption of 3 MWh. However, taking the manufacturer specific biomass consumption into account (1.2 kg_{dry}/kWh), the energy obtainable will be 21568 MWh (7189 families).

About CO_2 capture, considering a biochar composition of 80% carbon and 20% ashes and considering an average production of 50 kg of dry biochar every ton of biomass, the total CO_2 stored in the biochar obtained from the gasification of 1 ton of dry Arundo Donax is about 150 kg.

Therefore, considering the total ABG in marginal areas of the UTA district, the total annual carbon dioxide amount that can be stored physically using biochar is about 3882 ton/year. Biochar has multiple utilization, i.e. soil amendment and fertilizer, raw material for activated carbon production, filter media, carbon source for nutraceutical and pharmaceutical purposes [27-28]. The biochar produced through gasification can be re-used in the UTA district as soil amendment directly of Arundo Donax crops to enhance plant productivity [3].

4. CONCLUSIONS

Marginal wet areas of the UTA district have a massive potential for giant reed crop growing. The simulation results show a seasonal Arundo Donax productivity of 26 thousand of tons using 477.3 ha of marginal land close to Secchia river and canals. The gasification of this biomass was performed in a small scale gasifier power plant at partial electrical load mixing them with fir wood chips in order to avoid bridging issues in the hopper. In fact, the machine used in this work was designed to work with wood chips and the utilization of chipped Arundo Donax only it will be possible modifying the biomass supply system from the hopper to the reactor. However, the gasification of the mixed fuel was performed at partial load and a specific biomass consumption of 2.72 kg_{dry}/kWh was achieved. The overall electrical efficiency calculated was 7.72%, about a half of the nominal overall electrical efficiency, probably due to the partial electrical load applied. However, the calculated energy production was 9.5 GWh and the estimated CO_2 storage, achievable using biochar as soil amendment, is about 3.9 thousand of tons every year. Future studies will investigate the optimization of the biomass moving system and the behavior of the biochar applied as amendment on Arundo Donax crops.

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