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Bioenergy integrated systems and Small Plants Research activity

Francesco Martelli

P.Adami, D.Chiaramonti,D.Fiaschi ,S.Maltagliati,G.Riccio

University of Florence, ITALY

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Outline of presentation:

- ✓ The New Center For Renewable Energy in Florence & the active projects
- ✓ Small Scale power plant activity & testing (Falascaia)
- ✓ Micro Cogeneration System: preliminar study (Sambuca)
- ✓ Feasibility study of small-micro integrated plants
- ✓ Numerical modelling & simulation of critical equipments
- ✓ Regional Biomass Exploitation: technical & Economical evaluation

Dipartimento di Energetica "Sergio Stecco"- Università di Firenze

C.R.E.A.R.

Centro di Ricerca sulle Energie Alternative e Rinnovabili

Objective: *Coordinate and organize synergy research activity based on multidisciplinary of renewable Energy. Increase competition capability of Research groups.*

Activity: *Set up a laboratory to test and develop small power plants for distributed energy production; based on up to date techonolgy for biomass use, and other renewable source (wind, Geo, Solar..). Research project coordination.*

Members:*Dip. Energetica+3 Dip. Agricultural+Dip. Chemestry,Dip. Geology*

A number of completed and on-going biomass projects. Among others:

- ***BIOSIT** (GIS-Biomass resource assessment) – Life Programme*
- ***COMBIO** (Pyrolysis Oil – Emulsions for Heating) – 5PQ*
- ***OPRODES** (Renewable Energy Desalination) – 5PQ*
- ***TOSCANAPA** (Impianto macerazione canapa) – R.T.Progr.ITT*
- ***ENVIRONMENTAL IMPACT ASSESSMENT** (biomass, wind)*
- ***CROPENERGY** (Bioenergy production from Energy Crops) – 6PQ-STREP*
- ***BIOCHAIN** (Development of a bioenergy chaqin on the Amiata mountain)*
- ***BIO-FOOD-ENERGY FARM** (Demonstration project for the development of integrated food-energy farms)*
- *Other activities on **PELLETISATION TECHNOLOGIES**, pre-treatment, etc.*

.. moreover ...

- ***IMES** – EU-USA International Master Course on Bioenergy and Environment (Univ.di Firenze, Univ.di Aston, Univ.di Lisbona – Baylor, Arizona e Texas Univ.s)*

✓Experimental tests on the Falascaia Plant (*Lucca-Tuscany*)

The Falascaia plant has been designed for the power generation from urban wastes and biomass through a steam cycle

The tests have been performed while burning chipped pine and latifoglie triturate

Main Components:

- 2 Bubbling Fluid Bed reactors of 12 MWt each
- Steam turbine (Ansaldo), coupled with a generator ~ 5 MWe
- Emmission treatment of the exhaust: SNCR, cyclons, filter fly ash, scrubber

Plant Analysis: Objectives and Methodology

Objectives

- Recommendations for an optimal plant regulation
- Methodology of the teoretical-experimental tests

Analysis methodology

- Modelling of the plant and definition of the plant variables
- Performance variables set
- Experimental data acquisition
- Post-processing of data
- Regulation variables set
- Results and sensitivity analysis

AIR-PHOTOGRAPH of the PLANT

PLANT ANALYSIS

- **Modelling of the plant and definition of the plant variables**

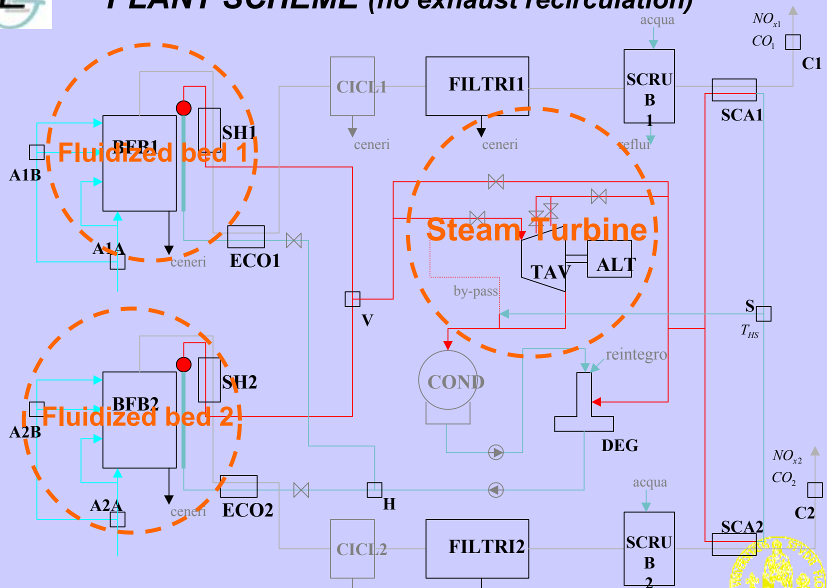
In the Falascaia plant, many variables are continuously monitored (temperatures, pressures, fluxes, et.) and measured. Others can be computed from the monitored ones, through the model developed:

measured variables + analytically computed variables

We determined the variables describing the performances and the ones that can be set to optimize the performance, i.e.:

performance variables + Controll variables

PLANT SCHEME (no exhaust recirculation)



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PLANT ANALYSIS

- **Performance variables set**

The monitoring operations and the regulation are concentrated on to the fluidized beds; the power generation isle can be regualted only through steam spillages. Thus, both the performances and the controll variables concern the reactors

Performance variables

$\eta_{combust}$, thermal duty, emissions (CO, NOx, organic contaminants), NH3 consumption

The controll variables are determined based on the plant model and on the sensitivity analysis. They are chosen among the measured and the analytically computed variables

plant scheme: measured variables

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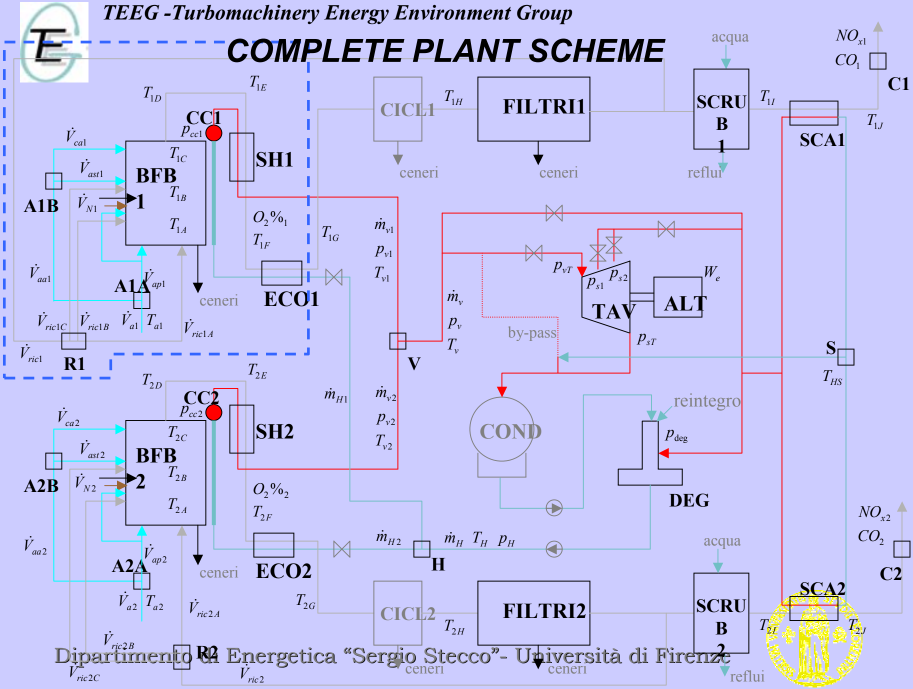
COMPLETE PLANT SCHEME



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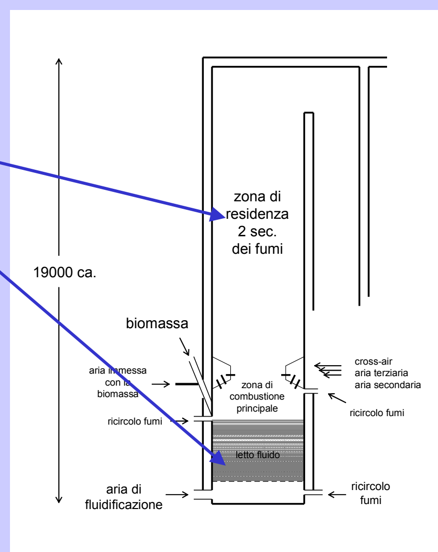
REACTOR SCHEME

- **Main Component:**
  - fluidized bed
  - residence zone of the exhaust (necessary for the waste combustion)
- **Air inlets (5):**
  - fluidizing air
  - biomass incoming
  - secondary air
  - tertiary air
  - cross-air
- **Ricirculation of the exhaust:**
  - into the fluidized bed
  - together with the biomass inlet
  - together with the secondary air



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EXPERIMENTAL TESTS AND ANALYSIS

- **Experimental data acquisition :**
  - steady working conditions
  - large range of thermal duty

⇒ ***Data corresponding to 23 performance variable monitoring have been collected in different working conditions and with different biomass humidity***

- **Post-processing of data** to determine the variables which are not measured

- **Controll variables set** choice

Controll variables:

1) biomass humidity, 2) air excess, 3) temperature of the main combustion zone, 4) total flux of the exhaust recirculation

- **Results and sensitivity analysis**

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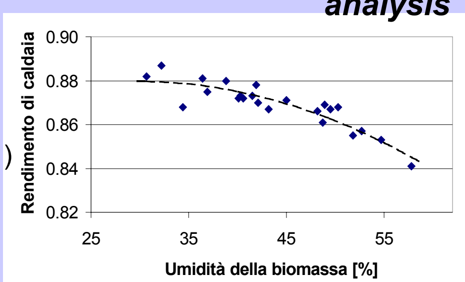
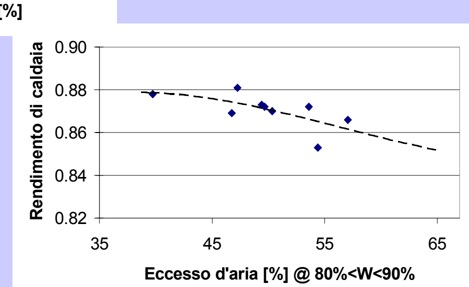
EXPERIMENTAL RESULTS: sensitivity analysis

1)


← ***Efficiency of the reactor decreasing with biomass humidity***

Efficiency of the reactor decreasing with air excess →

2)


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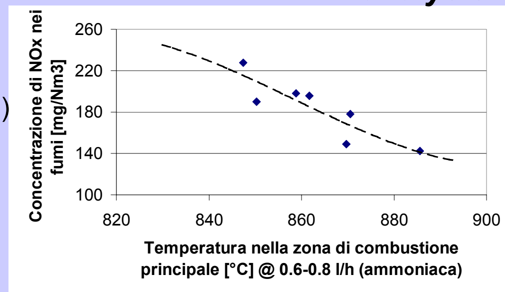
EXPERIMENTAL RESULTS: sensitivity analysis

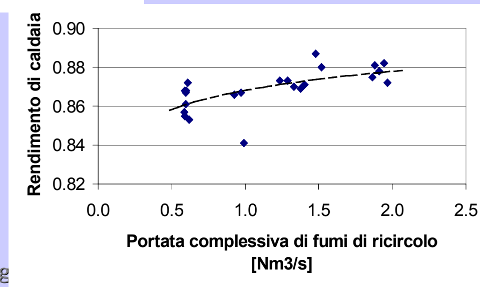
3)



← ***NOx emission decreasing with temperature***

Efficiency of the reactor increasing with the exhaust recirculation flow rate →

4)



CONCLUDING REMARKS

- **Recommendations for an optimal plant regulation**

The optimal values of the following parameters have been determined :

- **Biomass humidit, to increase the efficiency**
- **Air excess (measured through the O2 content monitored in the moist exhaust)**
- **Minimum value of the temperature in the main combustion zone, to limit the NOx formation, thus the NH3 employment**
- **Maximum value of the NH3 rate, less than 2 l/h, to take the NOx under the low limit**
- **Recirculation flow of the exhaust into the fluidized bed**
- **Minimum value of the fluidized bed temperature, to increase the efficiency**
- **No recommendations have been considered for CO, since the emission are low**

✓Micro Cogeneration System: preliminar study

(Sambuca- Tuscany)

BIOMASS MICRO COGENERATION SYSTEM IN AN INDUSTRIAL AREA OF TUSCANY CHIANTI HILLS :

❖ What chances to instal & operate a **300 – 600 kWe micro cogeneration system** in an existing industrial park of Tuscany Chianti hills ?

THERMODYNAMIC AND COSTS ANALYSIS

❖The study is based on the analysis of the local agricultural and industrial **wastes potential within an of up to 5 kilometres transport distance**, which defines the power plant size

❖The **optimisation of heat recovery, related to the local utilities**, was a further essential aspect which addressed the power cycle layout. The option of **providing heat for a local system of waste water treatment** was also considered and evaluated

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THERMODYNAMIC AND COSTS ANALYSIS

❖The possible options of electrical generator drivers such as **internal combustion engine** and Organic Rankine Cycle **(ORC)** were evaluated and compared

❖The **thermodynamic and costs analysis** was carried out referring to **four possible scenarios**, defined by the **availability of primary biomass fuel**. A sensitivity analysis to the variable cost of fuel was also performed in terms of payback period and Net Present Value

❖The study lead to the **conclusion** that **the investigated area might be an interesting site for installing a biomass micro cogeneration power plant**, with both energy and economic profitability for the local companies, especially if coupled with the water treatment system

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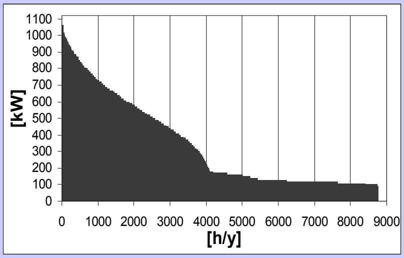
Users CHP demand and technical solutions

The Sambuca industrial park is a local system of SMEs (Small and Medium Enterprises) located in a rather flat and narrow Chianti valley on the sides of the Pesa river, nearby Florence-Siena highway



Heat duration curve in the Sambuca industrial park

HP1	*Industrial and agricultural (caseA) waste wood*	2655t/y
HP 2	*Industrial and agricultural (caseB) waste wood*	5400 t/y
HP 3	*Industrial and from selective collection waste wood*	2200 t/y
HP 4	*Agricultural (case A) and from selective collection waste wood*	3255 t/y

Biomass availability in the four possible operating conditions

Main goal *of this work is to show the economic feasibility of the proposed project*

Down-draft gasifier coupled to a gas engine for CHP production

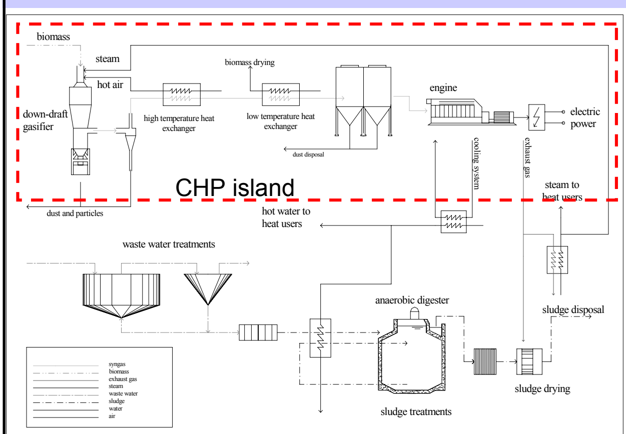


Table 2 – CHP thermodynamic data

	HP 1	***HP 2***	***HP 3***	***HP 4***
wt_{FP} [hrs/y]	7.500	7.500	7.500	7.500
W_{el} [kWe]	**317**	**679**	**313**	**431**
ηel[%]	23.5	25.3	26	26
η_{th}	31%	29%	35%	32%
$\eta_{th\,exh}$ [%]	15	14	16.8	15.6
$\eta_{th\,cool}$ [%]	19.5	18	21.6	20.1
$W_{th\,gasifier}$ [kWt]	1.504	3.005	1.321	1.844
$W_{th\,exh}$ [kWt]	203	377	202	258
$W_{th\,cool}$ [kWt]	264	483	260	333
$W_{th\,engine}$ [kWt]	467	859	462	591
$W_{th\,max\,used}$ [kWt]	**409**	**681**	**413**	**519**
$W_{st\,gasifier}$ [kWt]	58	178	49	72
E_{el} [MWhe/y]	2.381	5.095	2.350	3.230
$E_{in\,fuel}$ [MWht/y]	11.283	22.534	9.910	13.833
E_{th} [MWht/y]	3.067	5.110	3.101	3.896
$E_{th\,used}$ [MWht/y]	1.915	2.424	1.928	2.188
η_I [%]	38	33	43	39
LHV_{Bio} [kJ/kg]	14923	14628	15885	14912
LHV_{Syn} [kJ/kg]	4622	4493	5459	4982
w_{Bio} [%]	15.5	16.2	13.6	15.9
m_{Bio} [kg/s]	0.10	0.20	0.08	0.12

CHP plant based on ORC SYSTEM

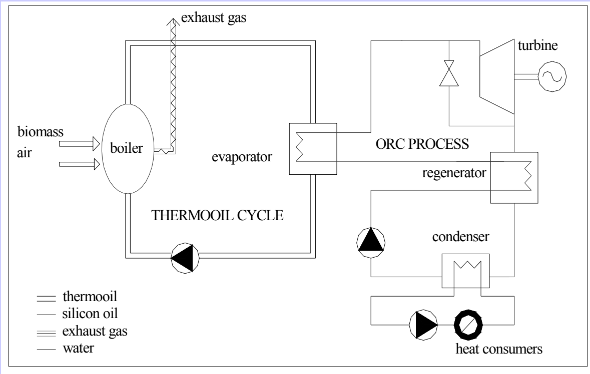


Table 3 – Main operating data of ORC in the two supposed case studies

	HP α	HP β
Biomass flow [t/y]	*6200*	*8300*
Biomass LHV [kJ/kg]	*15221*	*15317*
Electric effiicency [%]	*17*	*17*
Boiler efficiency [%]	*75*	*75*
Electric power [kWe]	*446*	*600*
Thermal power [kWh]	*2025*	*2800*
Working hours [h/y]	*7500*	*7500*

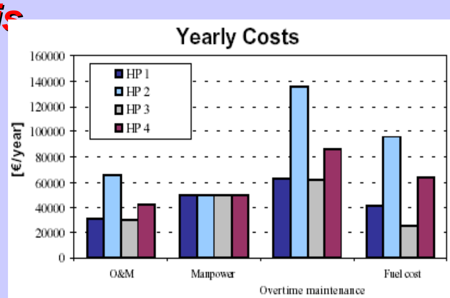
Economic analysis

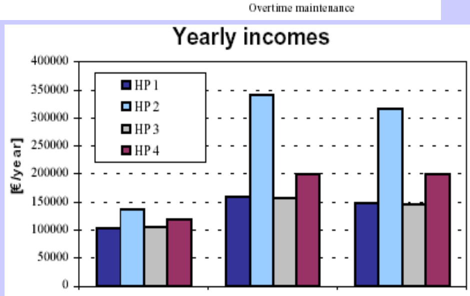
Investment costs of the proposed CHP in the four possible considered scenarios

CHP investment costs	**HP 1**	**HP 2**	**HP 3**	**HP 4**
Powerplant components (gasifier, cogenerator, heat exchangers, syngas cleanup system, generator, control system) [k€]	713.3	1526.0	703.9	967.5
Land purchasing [€]	60	60	60	60
Buildings, auxiliaries, biomass fuel storage [k€]	70	70	70	70
Heat distribution network [k€]	65.43	109.02	66.16	83.12
Total **[k€]**	**908.7**	**1765.1**	**900.0**	**1180.6**
Overtime after which additional maintenance costs are required [khrs]	40	40	40	40
CHP life [khrs]	112.5	112.5	112.5	112.5
Unit biofuel cost [€/ton]	15.5	17.8	11.4	19.6
Incomes taxes [%]	40	40	40	40
CHP lifetime [y]	15	15	15	15
Discount rate [%]	12	12	12	12
Inflation rate [%]	2.5	2.5	2.5	2.5

Financial parameters of the six possible CHP options

	NPV [k€]	**PBT [y]**	**IRR [%]**	**Incentive 25%**		
				NPV [k€]	**PBT [y]**	**IRR [%]**
HP1	373.6	6-7	20.1	600.8	4-5	28.7
HP2	770.1	6-7	20.6	1213.8	4-5	29.5
HP3	446.2	6-7	21.6	671.2	4-5	30.4
HP4	495.8	6-7	20.3	791.0	4-5	29.0
HPα	463.2	7-8	18.6	805.0	4-5	26.7
HPβ	705.7	6-7	20.8	1096.2	4-5	29.5



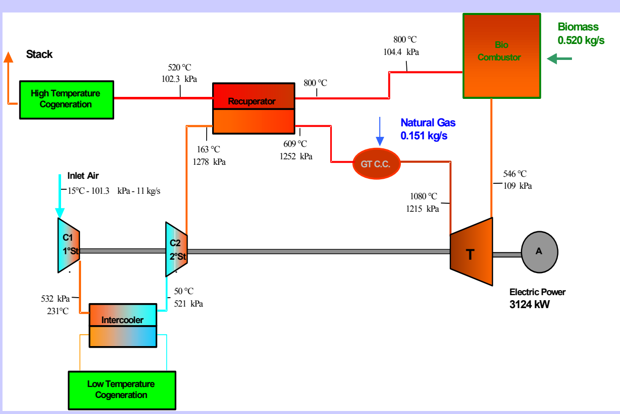


✓Feasibility study of small-micro integrated plants

- External Fired Gas Turbine Power Plant Fed by Solid Fuel
- Integrated micro-turbine & gasifier with FC & renewable energy supply

External Fired Gas Turbine Power Plant Fed by Solid Fuel

DCGT - Dual Combustor Gas Turbine



Technical Features

- **Gas Turbine Power Plant**
- **Dual Combustion:**

Internal Combustion of natural gas (or biofuel-ethanol) in GT comb. chamber

External Combustion of solid biomass in grate furnace or BFB at atm P

- **Intercooling**

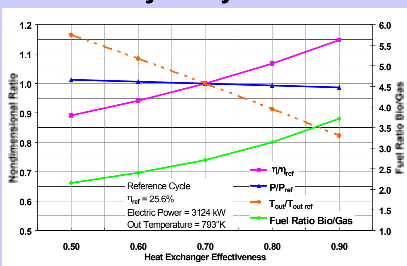
Performances

- Net Electric Power **3124 kW**
- Net Efficiency **25.6 %**
- Energy ratio Biomass/Natural gas **0.83**
- Cost per kWh of net electric Power **0.057€**

Advantages & Peculiarities

- Direct combustion of solid state biomass at atmospheric pressure
- Smaller size of the plant in comparison with a steam power plant
- Satisfactory Performances *(η = 25.6 %)*
- Wide cogeneration possibility *(T_{low} =231°C; T_{high}=520°C)*
- Competitive cost investment

Heat Exchanger Effectiveness Sensitivity analysis :

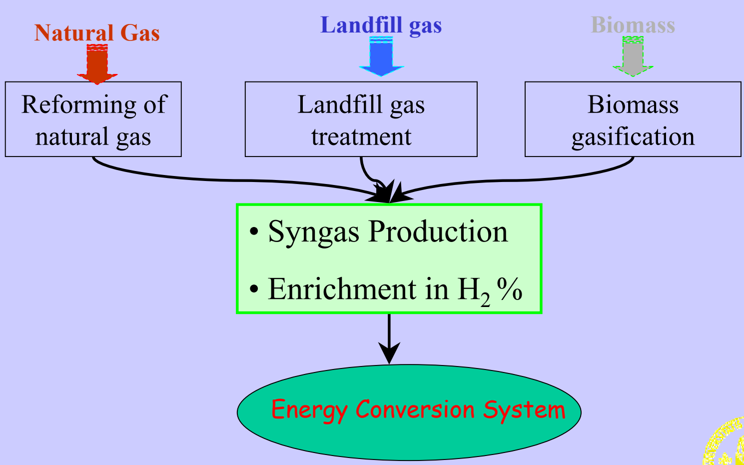


Key Points

- ***Combustion Systems***
- ***Heat Exchanger Technology***
- ***AutomaticBiomass Supply and Plant Control***

$$\varepsilon = \frac{T_{out-COLD} - T_{in-COLD}}{T_{in-HOT} - T_{in-COLD}}$$

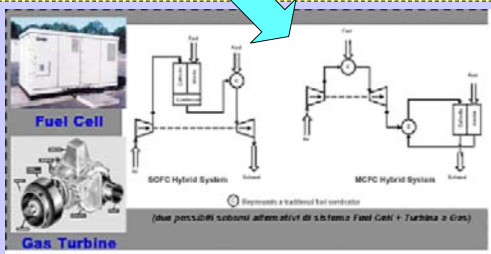
Integrated system for production and energy conversion of Renewable sources



Energy Conversion System

Energy Conversion System

- Reciprocal Engine (CHP)
- Micro GT / Fuel Cell integrated system
- R&D on Fuel Cell



✓*Numerical modelling & simulation of critical equipments*

- ***CFD of GT Combustion Chamber***

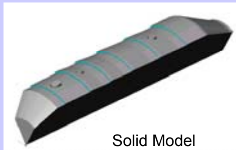
  Aerodynamic simulation of the liner: study of the swirler angle influence

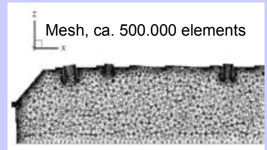
- ***Biomass gasification kinetics model***

  A two-phase one-dimensional model

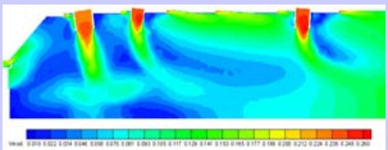
CFD of GT Combustion Chamber

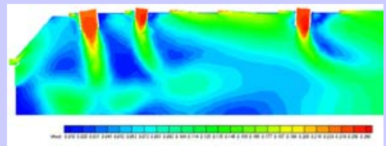
Aerodynamic simulation of the liner: study of the swirler angle influence

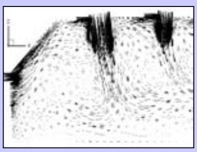




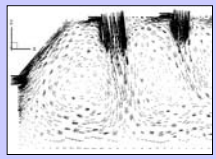
Vmod







ϑ flusso 30°

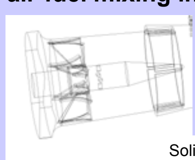


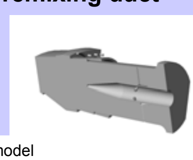
ϑ flusso 45°

CFD of GT Combustion Chamber

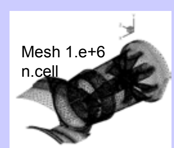
Detailed simulation: air-fuel mixing in premixing duct

Geometry

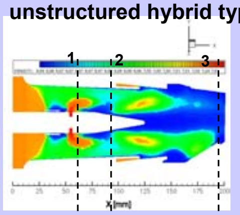


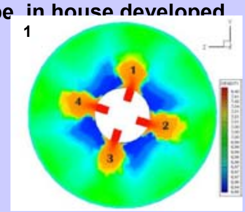


Solid model



Computation by the CFD code Hybflow: 3-D "Full-Navier Stokes" finite volume code of unstructured hybrid type, in house developed





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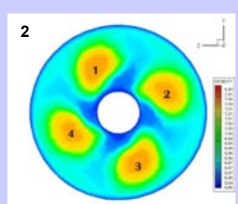
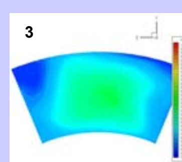




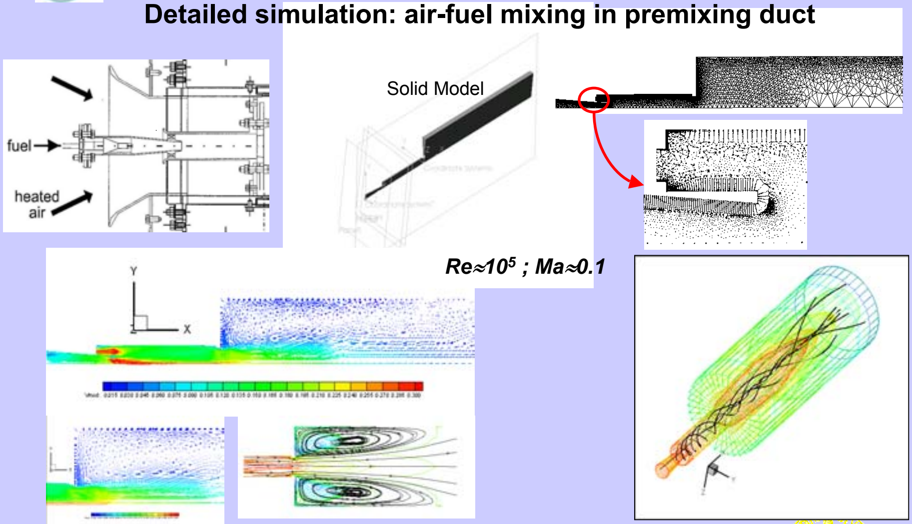
Outlet section

- **Air/fuel Mixing evaluation: *std (fuel conc.)***
- **Aerodynamic performances**

Study of modifications

Tuning of simplified design model

CFD of Lean Premixed Prevaporised (LPP) injection system
Detailed simulation: air-fuel mixing in premixing duct



Streamlines e pressione statica at the combustion volume inlet

❖ *A two-phase one-dimensional biomass gasification kinetics model*

Operating environment: bubbling fluidized beds

Model type: one-dimensional

Calculatied parameters

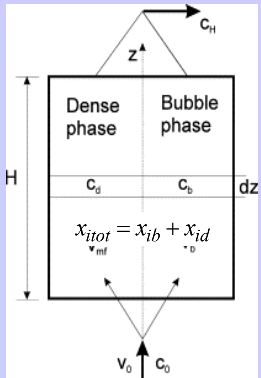
- temperature along the reactor axis
- concentration gradients along the reactor axis
- considers two phases, a bubble and a dense phase and accounts reaction kinetics in the dense phase
- mass transfer between the two phases and a quantitative estimation of local bubble and particle properties

Model's optimisation parameters

- ER (Equivalence Ratio)
- Reactor pressure
- Bed height
- Gas velocity

Mathematical one-dimensional model for the fluidized bed reactor

Double – phase model:
- *dense phase* (gas plus solid particles)
- *bubble phase* (mainly gaseous with much lower solid matter)



- *two-phase* reactor modeled as the sum of several elemental reactors of d*z* thickness
- Differential equations are solved vs. temperature and syngas composition, along the gasifier axis, for both dense and bubble phases

The gas flow entering the reactor at v_0 speed is splitted into two phases: the dense phase, (minimum fluidization velocity v_{mf}), and the bubble phase, (the velocity is $v_0 - v_{mf}$)

overall mass balance for bubble and dense phases

$$(v_0 - v_{mf})\frac{dC_b}{dz} + v_{mf}\frac{dC_d}{dz} + r(1-\varepsilon_b) = 0$$

Molar concentration of the i^th^ component into the two phases

$$C_{id} = \frac{x_{id} \cdot n_b}{(1-\varepsilon_b)\cdot V_{tot}} \quad \text{Dense} \qquad \text{Bubble} \quad C_{ib} = \frac{x_{ib} \cdot n_b}{\varepsilon_b \cdot V_{tot}}$$

Evaluation of the overall reaction kinetics

From one mole of a generic biomass $CH_\alpha O_\beta$ (d="dense", b="bubble", tot="dense+bubble", x_i="i^th^" specie concentration in gas):

$CH_\alpha O_\beta + y\,O_2 + z_{tot}\,N_2 + w\,H_2O = x_{1\,tot}C + x_{2\,tot}\,H_2 + x_{3\,tot}\,CO + x_{4\,tot}\,H_2O + x_{5\,tot}\,CO_2 + x_{6\,tot}\,CH_4 + z_{tot}N_2 = (x_{1\,d})\,C + (x_{2\,d} + x_{2\,b})\,H_2 + (x_{3\,d} + x_{3\,b})CO + (x_{4\,d} + x_{4\,b})\,H_2O + (x_{5\,d} + x_{5\,b})\,CO_2 + (x_{6\,d} + x_{6\,b})\,CH_4 + (z_d + z_b)N_2$

Chemical gasification reactions considered in the mathematical model:

1. $C + CO_2 = 2CO$
2. $C + H_2O = H_2 + CO$
3. $C + 2H_2 = CH_4$
4. $H_2O + CH_4 = CO + 3H_2$

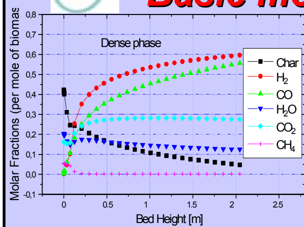
Serial effects of chemical kinetics and mass transfer limit the gasification speed: Then, the rate of the i^th^ chemical specie follows (electrical model analogy):

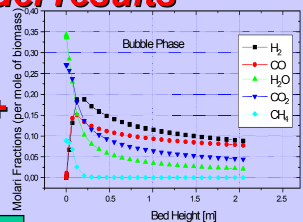
$$v_i = \frac{v_{it} v_{ikin}}{v_{it} + v_{ikin}}$$

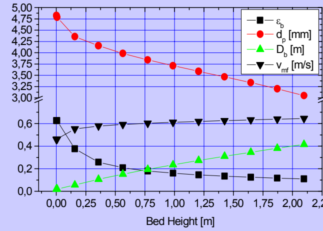
The temperature has been evaluated by a thermal balance along each of the elemental reactors into which the fluidized bed has been divided (time interval t_{j+1}-t_j):

$$\sum_{i_{tot}=1}^{ns} x_{i_{tot}}(t_j) h_{i_{tot}} + \sum_{i_{tot}=1}^{ns} x_{i_{tot}}(t_j) h_{fi_{tot}} = \sum_{i_{tot}=1}^{ns} x_{i_{tot}}(t_{j+1}) h_{i_{tot}} + \sum_{i_{tot}=1}^{ns} x_{i_{tot}}(t_{j+1}) h_{fi_{tot}} + q_l(t_j)$$

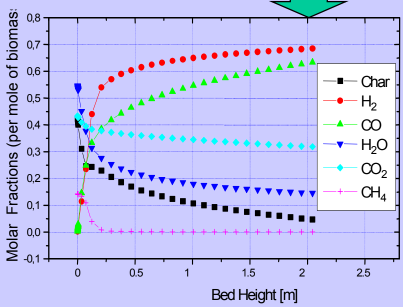
Basic model results







Bubble phase fraction, particle diameter, bubbles diameter and minimum fluidization velocity



Biomass composition (sawdust)	$CH_{1.41}O_{0.59}$	λ	3
Humidity (dry basis)	10 %	**Primary fragmentation factor n_1**	1.1
ER	0.33	**Secondary fragmentation factor n_2**	1.8
Oxidizer	air	**Oxidizer inlet speed v_o**	1 m/s
Bed Height	2.1 m	**Reactor wall thickness**	0.25 m
Bed diameter d_g	1.30 m	**External convection**	10 W/m^{2}K
Initial char particles diameter	5 mm	**Wall conductivity**	0.1 W/m K
Char density	1500 kg / m^3	**External temperature**	30 °C
Inert particles diameter	800 µm	**k_{at} (elutriation coefficient)**	$5 \cdot 10^{-6}$
Inert particles density	2600 kg/m^3	**Gasifier pressure**	1.013 bar

✓Regional Biomass Exploitation:

technical & Economical evaluation

BIOSIT

GIS-based planning tool for greenhouse gases emission reduction through biomass exploitation

Supported by the European Commission
LIFE-Environment demonstration projects

PARTNERSHIP

DE - Dipartimento di Energetica "S.Stecco" Florence University *coordinator*

DEART - Dipartimento Economico Agrario Risorse Territoriali Florence University

ETA – Energy-Trasports-Agricolture, Company

BIOSIT

GIS-based planning tool for greenhouse gases emission reduction through biomass exploitation

Objective of the project: to develop an innovative tool, based onto the Territorial Information System, to support the biomass management for energy production in Tuscany.

The specific objectives are the following:

1) Promotion and sustainable deevlopment of biomass to energy plants;

2) Reduction of atmospheric pollutants emission and CO emission;

4) Valorisation of the territory, recovery of marginal areas;

5) Improved management of forestry and agricultural land

6) Integration between rural and urban areas

Action 1: GIS-based analysis of biomass production in Tuscany

Biomass-to-energy resources typologies
Present resources
- Forestry residues (from felling operations)
- Wood industry residues
- Agricultural residues: fruit trees pruning and herbaceous residues from ceral cultivations
Potential resources
- Short Rotation Forestry (SRF)
- Energy Crops (herbaceous)

IFT (Tuscany Forestry Inventory)+Corine Land Cover+Industry census

(territorial distribution of the forestry species, cultivations industrial activities)

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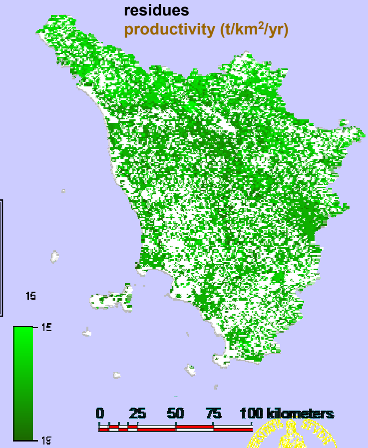
Productivity analysis for each specie and/or activity

Productivity: t/km^2/yr

Example::
cereal residues and forestry residues
productivity (t/km^2/yr)



TEEG -Turbomachinery Energy Environment Group

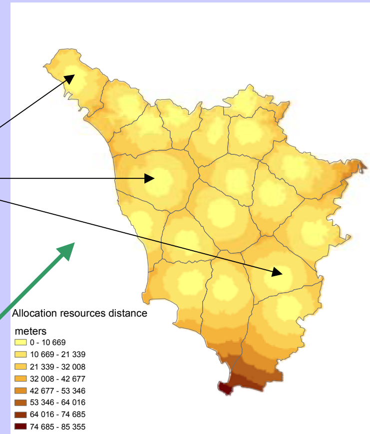
Action 2: Design and implementation of a computational algorithm of the biomass total cost (from the collection to the plant); supply basins definition

1) GIS implementation of the computational algorithm of the toatl costs: production, collection, stocking and transport to the stockpile centre

2) 19 stockpiling center have been identified, with startegic characteristics (existing infrastructures, industrial areas)

3) Trasport costs optimization

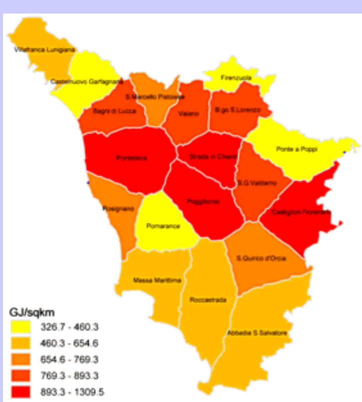
Optimal surface extension of the 19 supply basins



TEEG -Turbomachinery Energy Environment Group

Action 3: GIS-based evaluation of the energy potential and the optimal plant distribution

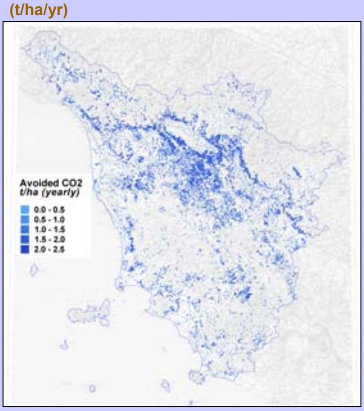
Example:
energy potential of agricultural and forestry residues
$GJ/km^2/yr$)



SUPPLY BASINS	INSTALLABE POWER (MWE)
Villafranca Lunigiana	6.55
Firenzuola	2.0
Castelnuovo Garfagnana	4.675
S.Marcello Pistoiese	4.15
Bagni di Lucca	7.775
B.go S.Lorenzo	6.45
Vaiano	3.77
Ponte a Poppi	5.26
Strada in Chianti	11.85
Pontedera	14.8
S.G.Valdarno	7.475
Poggibonsi	10.03
Pomarance	4.30
Castiglion Fiorentino	10.7
Rosignano	5.25
S.Quirico d'Orcia	8.4
Massa Marittima	4.77
Roccastrada	8.3
Abbadia S.Salvatore	9.75
TOTAL	136.255

Action 4: Evaluation of the environmental and social impact of the bioenergy sector

Example:
CO2 avoided through the energy conversion of biomass from agricultural reasidues instead of fossil fuels
(t/ha/yr)



Employment impact (# of workers) for biomass collection and transport in the bioenergy sector