Status and Trends of Advanced Thermal Treatment of Solid Waste

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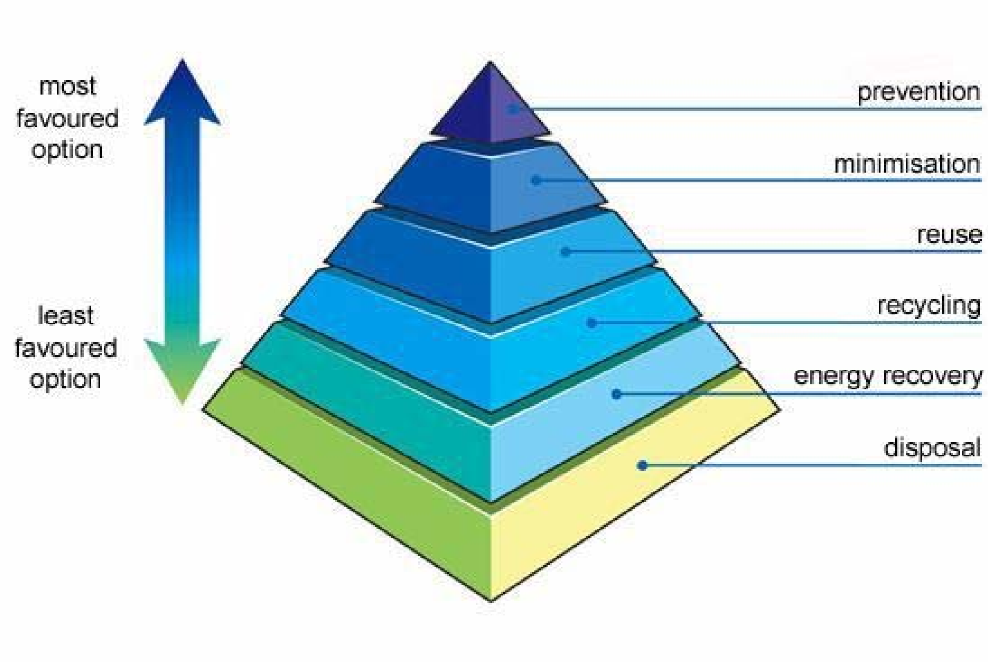
waste hierarchy



Waste disposal is a key issue in highly urbanized areas whose management has vital

environmental, economical and social implications

Waste management requires implementation of effective strategies based on the integration of waste reduction coupled with advanced waste disposal

Waste disposal is most often associated with energy and/or material recovery

The solid waste management scenario in the recent years has shifted towards a more sustainable approach.

modelling tools and approaches used for supporting waste management decisions

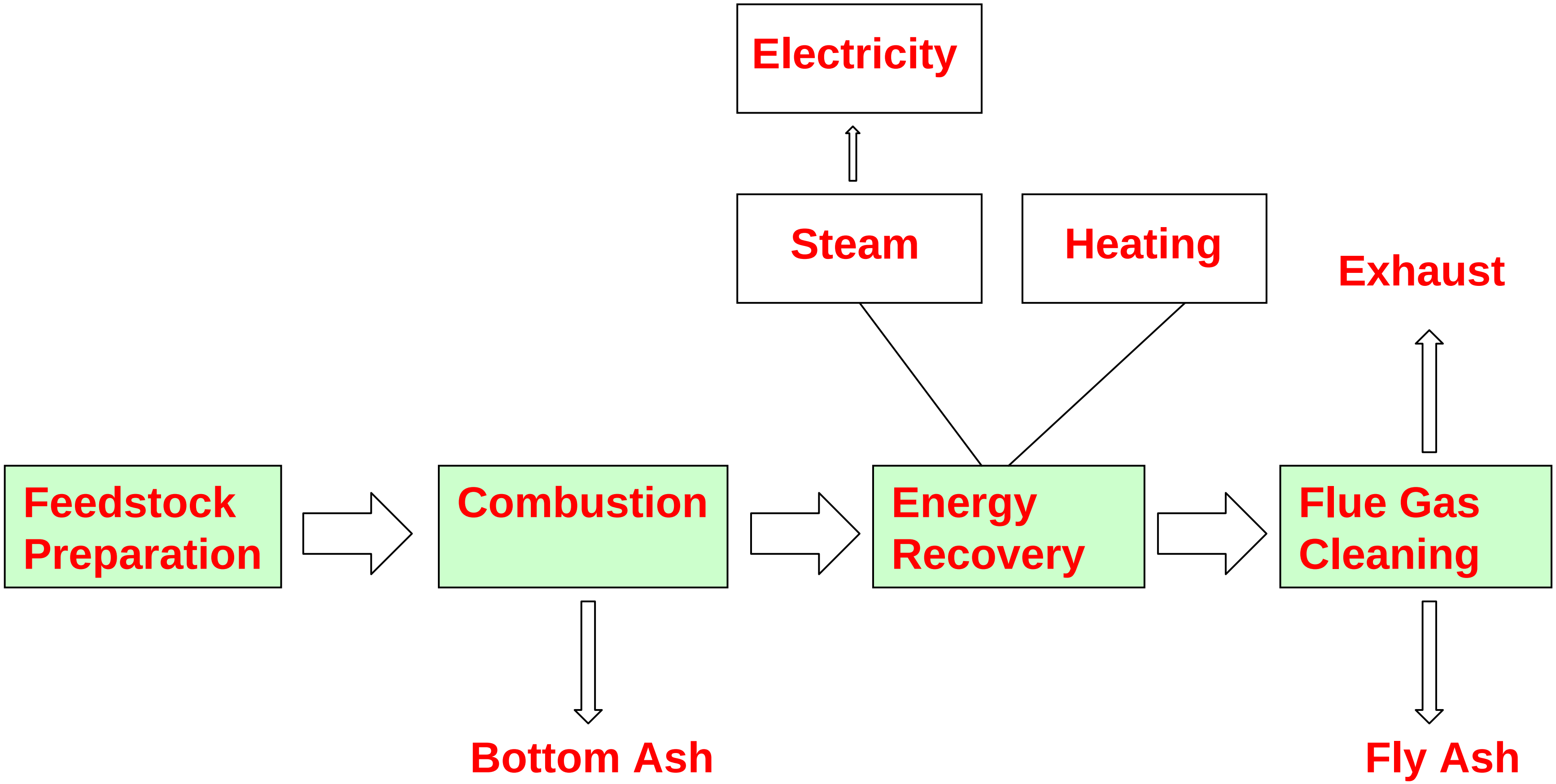
- ✓ Environmental Impact Assessment
- ✓ Life Cycle Assessment (LCA)
- ✓ Different types of Material Flow Analysis (MFA)
- ✓ Cost- Benefit Analysis (CBA)
- ✓ Life Cycle Costing (LCC)
- ✓ Risk Assessment
- ✓ Exergy Analysis, Entropy Analysis

all systems analysis methods

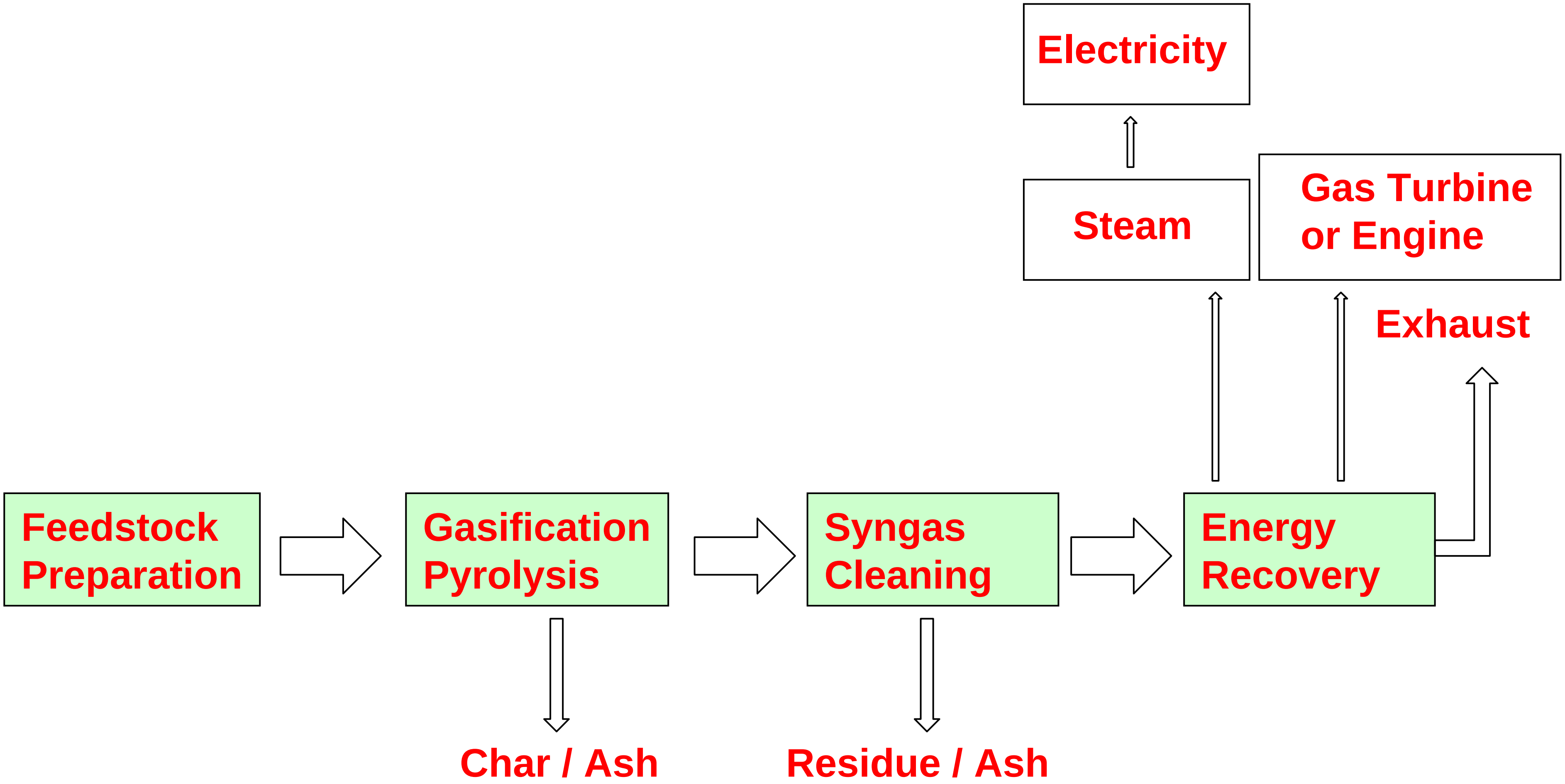
Different alternative technological options can be adopted for thermal treatment of solid waste :

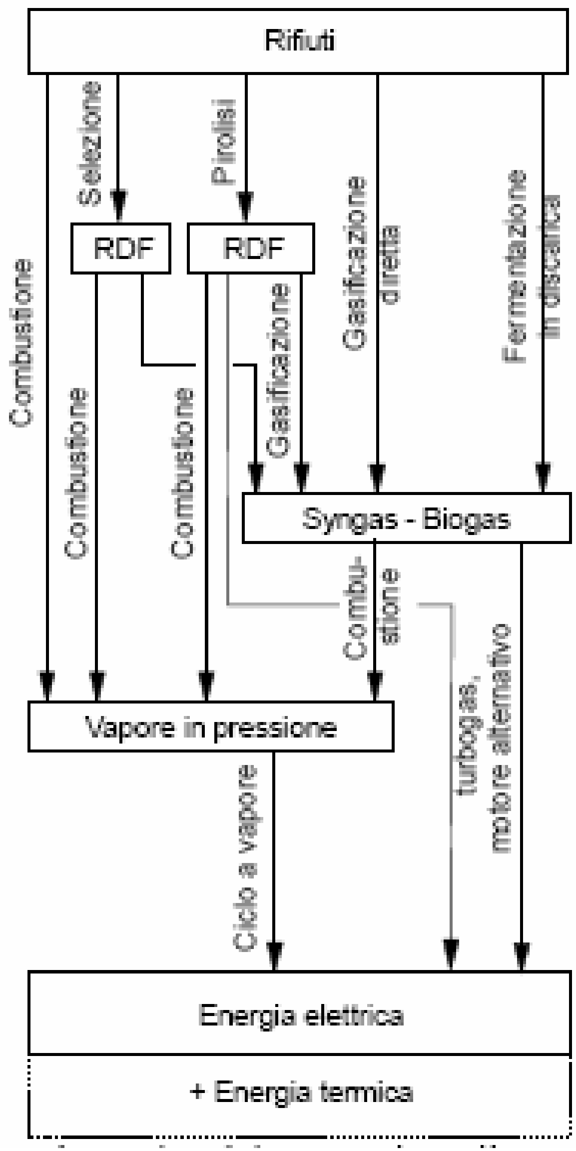
- direct combustion of waste (or waste-derived fuel)
- co-firing of waste with fossil fuels in existing non-dedicated plants
- pyrolysis/gasification of waste followed by syngas combustion

Direct combustion of waste (or waste-derived fuel)



Advanced thermal technologies: gasification/pyrolysis





- **direct combustion** of waste (or waste-derived fuel) or co-firing of waste with fossil fuels in existing non-dedicated plants. Waste derived fuel is a material characterized by an increased level of calorific value produced from solid waste through a number of different processes (separation at source; sorting or mechanical separation; size reduction - shredding, chipping and milling; separation and screening; blending; drying and pelletising; etc).

- **pyrolysis/gasification of waste followed by syngas combustion**

- **biotechnological treatment of waste followed by biogas combustion.**

Pros and cons of advanced thermal technologies

Pros

- ✓Reduced air emissions during syngas production
- ✓Reduced CO2 generation associated with syngas production
- ✓Vitrification of ash can be promoted
- ✓Production of dispatchable energy carriers from waste
- ✓Better environmental perception

Cons

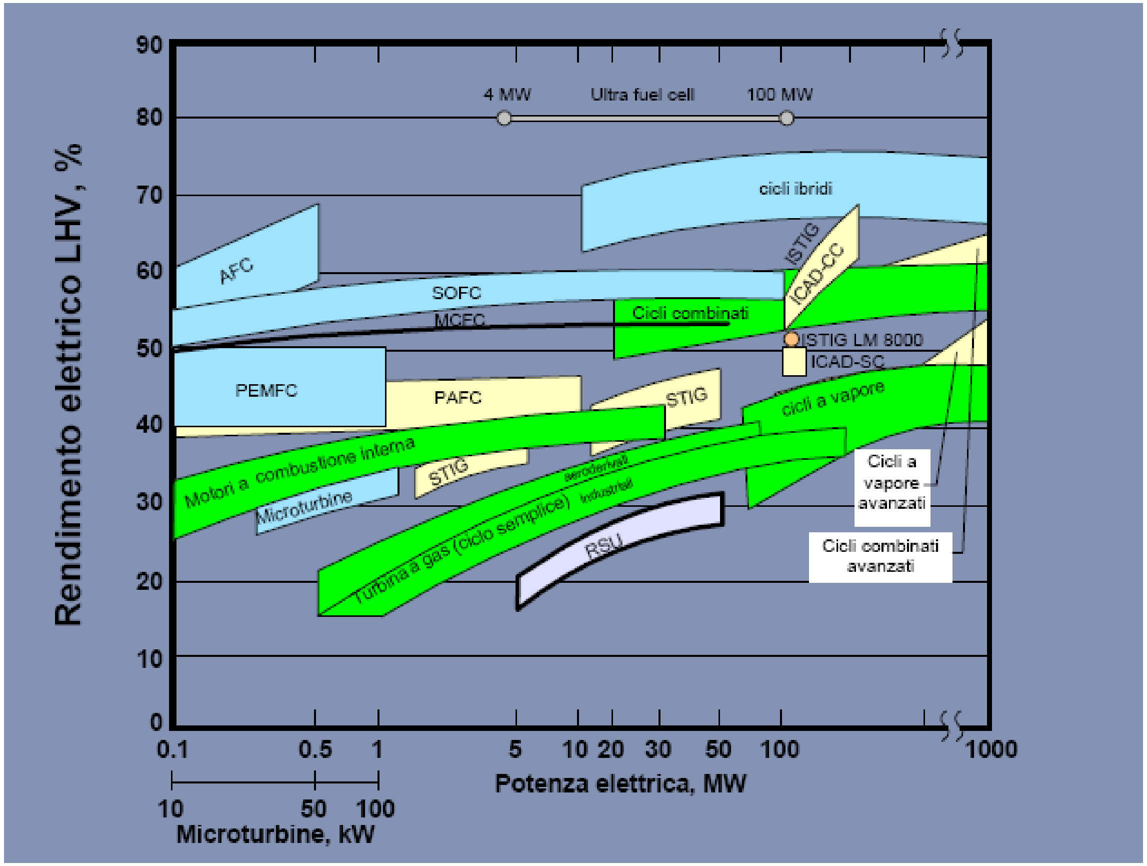
- ✓Syngas must be cleaned, leaving residues
- ✓CO2 formed when syngas burned
- ✓Vitrification has high energy requirements
- ✓Often lower energy recovery efficiency than conventional combustion systems
- ✓No real environmental advantages over combustion if syngas is used for heating

Key criteria for thermal treatment selection

- ✓ environmental impact
- ✓ economics
- ✓ plant availability/reliability

Waste co-firing with fossil fuels in large-scale combustion plants provides a mean to benefit from scale economy to improve the economics of advanced flue gas cleaning on waste disposal in existing plants

RDF combustion plants are characterized by a relatively low conversion efficiency



- beneficial aspects :

  - ✓ conversion efficiency higher than that obtained by using dedicated waste combustion plants

  - ✓ possible beneficial synergistic effects during coal/biomass/waste combustion

  - ✓ availability of advanced flue gas cleaning systems

- what is required:

  i. multi-fuel feeding
  ii. high degree of operating flexibility
  iii. careful measure and control of process parameters
  iv. pre-processing of waste material

⬇

Barriers to be overcome are the issues related to the whole chain of fuel supply for co-firing, optimizing combustion process involving multi-fuels, and ways of optimizing its economic, environmental and logistic consequences.

Integration of fossil fuels, biomass and non-toxic waste into a multifuel-based heat and/or energy supply system for any co-firing operation is required by plant operators who are interested in:

- ✓ maximizing the profit
- ✓ keeping the equipment trouble free over long periods of time (e.g., to prevent equipment corrosion from burning high-chlorine waste)
- ✓ keeping the flue gas emissions below limits
- ✓ keeping the ash properties such that they comply with the requirements for cheap disposal or a productive end-use

Pollutants from waste thermal treatment

✓Species inherently associated with the waste:

heavy metals, sulphur, nitrogen, chlorine

✓Species generated as a consequence of the unfavourable course of thermal processes: PICs (products of incomplete combustion)

polyclycic aromatic hydrocarbons

polychlorinated dibenzo-dioxins and dibenzofurans (PCDDs/PCDFs)

mixed brominated/chlorinated dioxins

unconverted carbon

✓Solid particulate

Increasing attention to fine ($PM_{2.5}$) and ultrafine ($PM_{0.1}$) particles

Factors affecting emission

- ✓ Composition and properties of waste
- ✓ Reaction conditions
- ✓ Time/temperature history of reacting material

Composition and properties of waste

Rapid changes in waste composition properties related to the intrinsic heterogeneity of the material or associated with poor feeding conditions may cause combustion upsets leading to an increase of emissions

Table 1. Typical composition of MSW by material

	Percentage by weight	Percentage by volume
Pulp and paperboard	37.5	37.0
Glass	6.7	2.3
Ferrous metals	6.3	8.8
Aluminum	1.4	3.1
Plastics	8.3	18.3
Rubber and leather	2.4	5.8
Textiles	2.8	5.4
Wood	6.3	5.9
Food wastes	6.7	2.7
Yard wastes	17.9	9.2
Other	3.7	1.5
Totals	100.0	100.0

possible strategies:

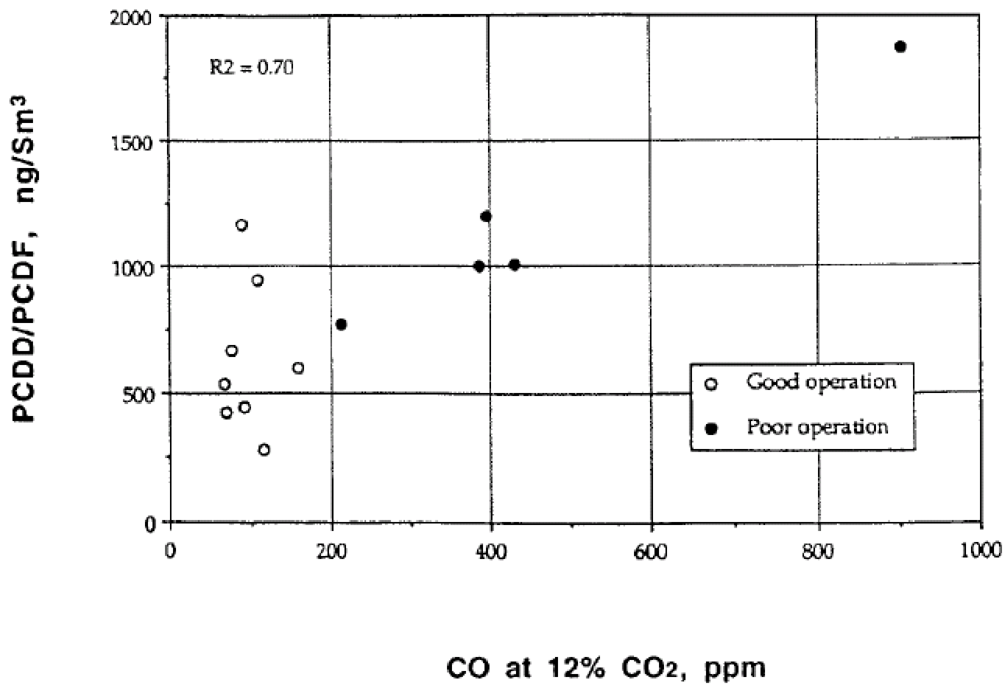
- to controll/produce waste of better controlled composition
- to blend or mix waste prior to combustion

to reduce variations in: heating content, volatile matter and moisture content

Reaction conditions

Municipal solid waste combustion conditions in a spreader stoker combustor were varied to provide good, poor and very poor combustion conditions as determined by flue gas concentration of CO

J.D. Kilgroe and A. Finkelstein: Int. Conference on Municipal Waste Combustion, Vol.2 EPA-600/R-92-052b (NTIS PB92-174671) p. 5°-67 (1992)



Municipal solid waste combustion conditions in a spreader stoker combustor were varied to provide good, poor and very poor combustion conditions as determined by flue gas concentration of CO

Organic concentrations at spray dryer inlet, Mid-Connecticut test program

Combustion conditions	Good combustion (Inter. load)	Very poor combustion (Inter. load)	Good combustion (Normal load)	Poor combustion (Normal load)
Test numbers	2, 10	5	8, 9, 11	3, 4, 7
SD Inlet				
Temp. (°C)	192	189	194	199
CO (ppm)	93	903	83	344
THC (ppm)	2.5	52	3	14
HCl (ppm)	450	469	461	430
SO_2 (ppm)	186	169	179	189
NO_x (ppm)	185	149	185	168
PM (mg/Sm^3)	4990	4460	4210	4050
Organics (ng/Sm^3)				
PCDD	228	580	125	196
PCDF	579	1280	591	732
CB	6050	15 800	5480	6940
CP	14 300	114 000	14 300	24 100
PCB	20	20	33	11
PAH	7330	112 000	16 500	53 900
Total organics	28 500	242 000	37 000	85 900
FF Outlet				
Temp (°C)	224	220	271	264
HCl (ppm)	19	21	54	19
SO_2 (ppm)	92	132	112	19
PM (mg/Sm^3)	4.9	3.9	5.1	5.8
Organics (ng/Sm^3)				
PCDD	0.13	0.37	0.33	0.37
PCDF	0.11	1.12	0.39	0.34
CB	53	754	228	110
PCB	ND	ND	19	12
CP	64	3240	3310	1882
PAH	2280	7730	3310	1882
Total organics	2400	14 000	3800	2200
VOC (ng/Sm^3)	102 000	3 370 000	16 000	632 000

time/temperature history of reacting material

This is accomplished by careful tailoring the time-temperature-oxidation history of the waste by proper space- and time-sensitive control of process temperature and mixing/segregation of heterogeneous and homogeneous phases

Prevention of emissions of the different classes of pollutants requires different and complementary strategies

✓Species inherently associated with the waste may be managed by pre-processing of the waste:

waste selection

waste benefication

pyrolysis/gasification of raw or pre-processed waste followed by syngas cleaning

✓Species generated as a consequence of the unfavourable course of thermal processes: PICs (products of incomplete combustion):

accurate process control

✓Solid particulate

waste selection

waste pre-treatment

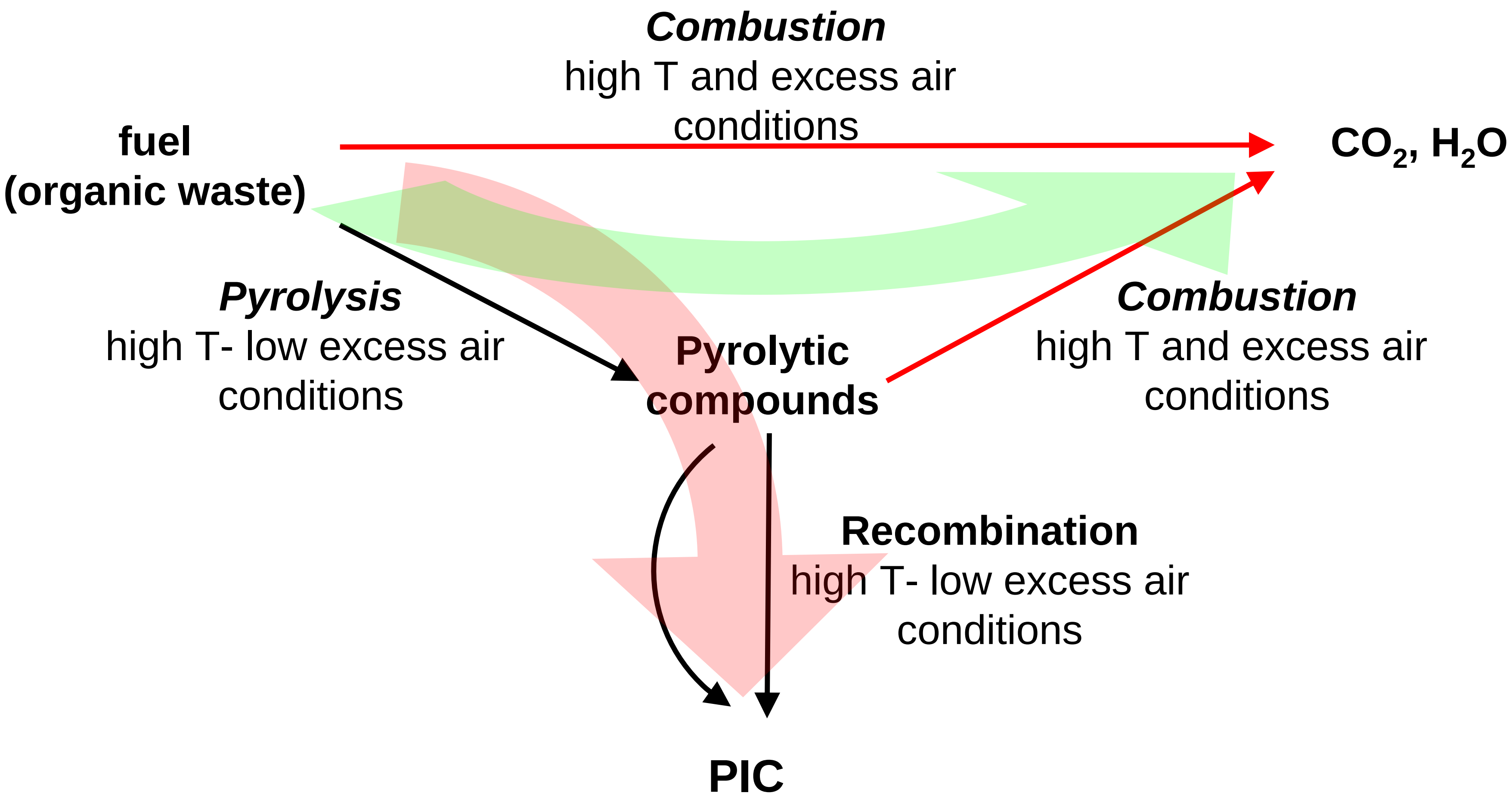
accurate process control

Flue gas cleaning complements fuel pre-processing and tailoring of thermal treatment processes to achieve effective and robust control air pollutant emission

- ✓ wet and dry scrubbing systems
- ✓ electrostatic precipitators
- ✓ fabric filters baghouse
- ✓ injection of calcium based reagent, limestone($CaCO_3$), lime (CaO) or hydrated lime ($Ca(OH)_2$), into the fournace or into the flue gas duct
- ✓ selective non-catalytic reduction of NOx

all these air pollution control technologies are common well estabished strategies which require the engineering optimization of the total gas cleaning process

Role of the parallel course of pyrolytic and oxidative processes in the formation of PICs (Products of Incomplete Combustion)



Prevention of PICs emission requires accurate control of thermal treatment processes

The nature of combustion by-products is determined by the chemicals that are treated and the conditions under which they react

The “Chemical reaction zone theory” proposed by Dellinger and Taylor (1998) for pollutant formation and destruction

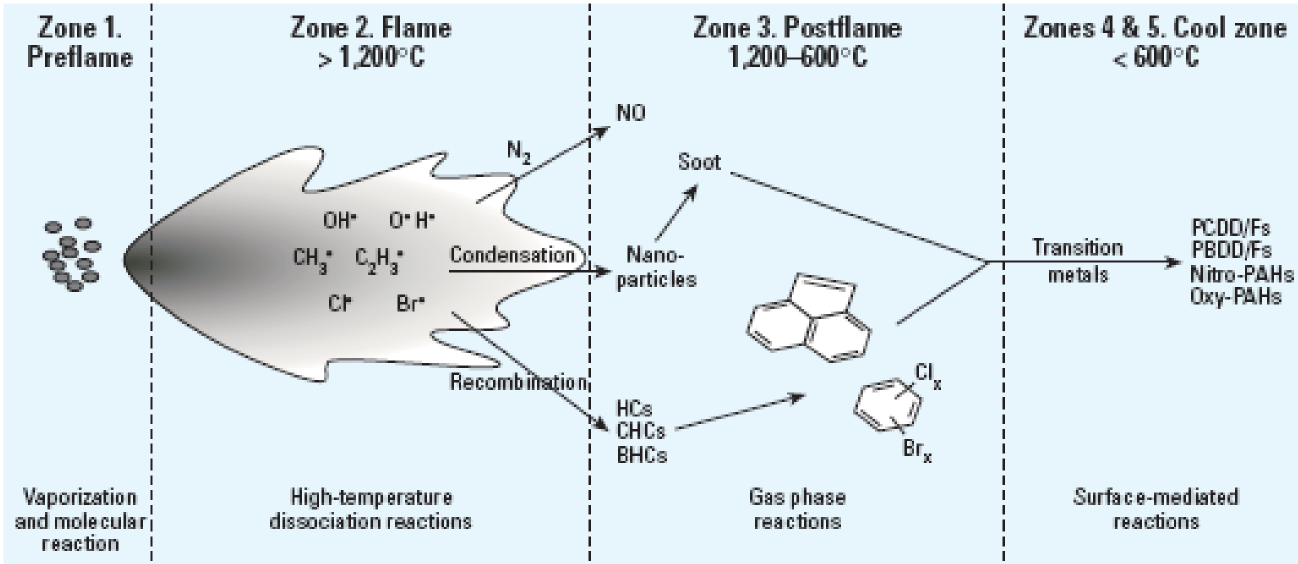


Figure 1. Combustor reaction zones. Zone 1, preflame, fuel zone; zone 2, high-temperature, flame zone; zone 3, postflame, thermal zone; zone 4, gas-quench, cool zone; zone 5, surface-catalysis, cool zone. PBDD/Fs, polybrominated dibenzo-*p*-dioxins and dibenzofurans. Reaction products from upstream zones pass through downstream zones and undergo chemical modifications, resulting in formation of new pollutants. Zone 2 controls formation of many "traditional" pollutants (e.g., carbon monoxide, sulfur oxides, and nitrogen oxides). Zones 3 and 4 control formation of gas-phase organic pollutants. Zone 5 is a major source of PCDD/Fs and is increasingly recognized as a source of other pollutants previously thought to originate in zones 1–4.

Zone model - Dellinger B, Taylor PH. 1998. Chemical aspects of combustion of hazardous wastes. Cent Eur J Public Health 6:79–87

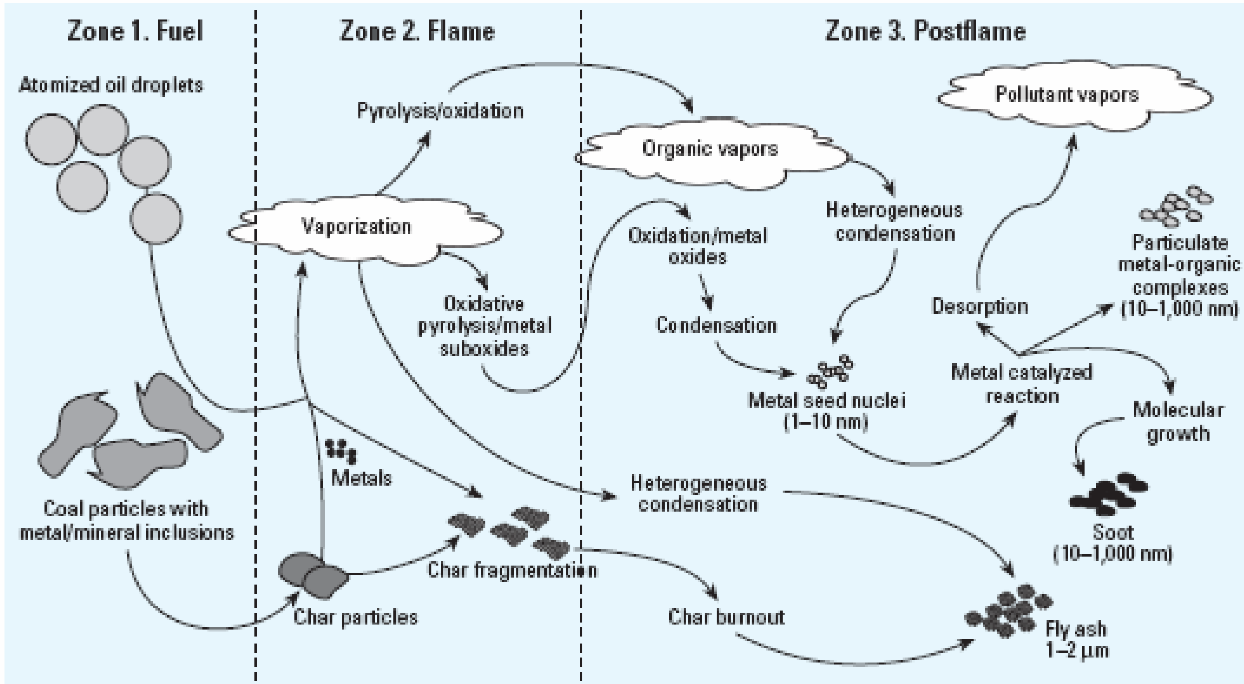


Figure 2. Nanoparticle formation/growth and mediation of pollutant-forming reactions in combustion systems. The combustor reaction zones described in Figure 1 effect particle formation as well as gas-phase pollutant formation. Metals and other refractory compounds are vaporized in the flame zone. They can recondense as cluster or seed nuclei in the postflame zone, where they catalyze further particle growth and pollutant formation in the cool zones.

S.A. Cormier, S. Lomnicki, W. Backes and B. Dellinger, Environmental Health Perspectives, 810-817 Vol. 114, N. 6, 2006

The non-linearity of reaction pathways requires good ability to handle the uncertainty related to the use of unsorted (or poorly sorted) combustible materials

In this framework the use of waste material makes even more critical this aspect as a result of its composition and properties.

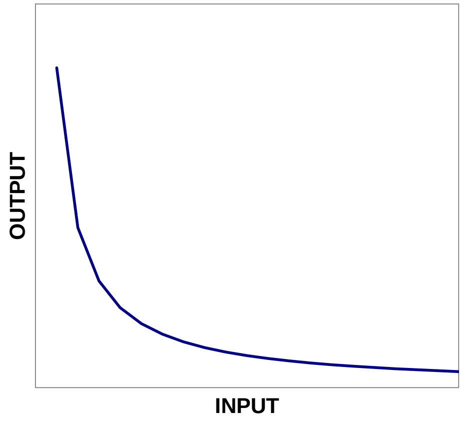
In particular waste or waste-derived fuels are both high volatile fuels characterized by high production of tar and condensed phases

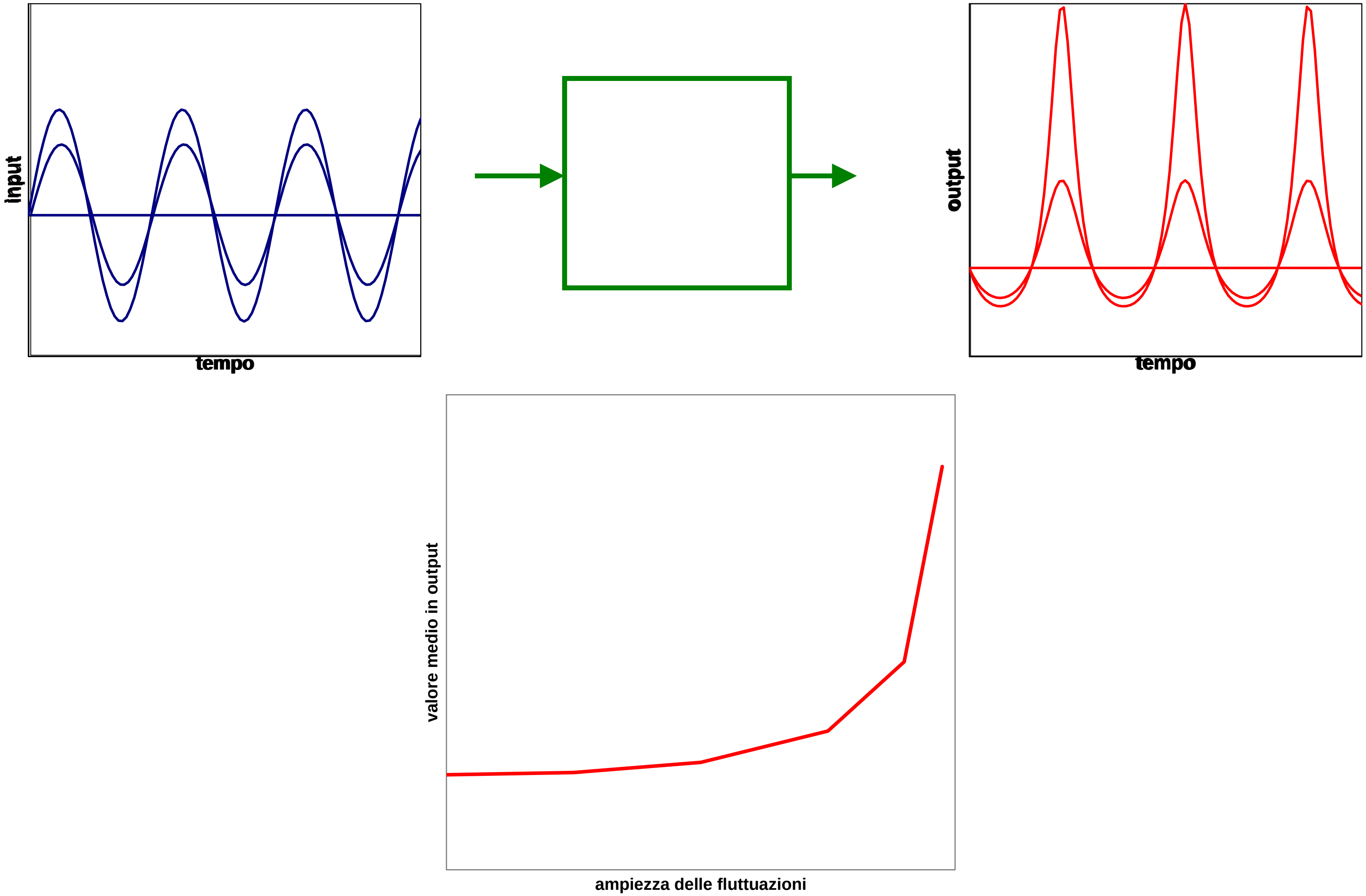
An example:

INPUT = air/fuel ratio
OUTPUT = Emission of PICs

Assume, for simplicity:

$$\mathbf{EI} = \frac{\mathbf{1}}{\mathbf{AC}}$$




input
tempo
output
tempo
valore medio in output
ampiezza delle fluttuazioni

Relevance of using advanced fast time- and space-resolved process diagnostics to monitor reaction conditions

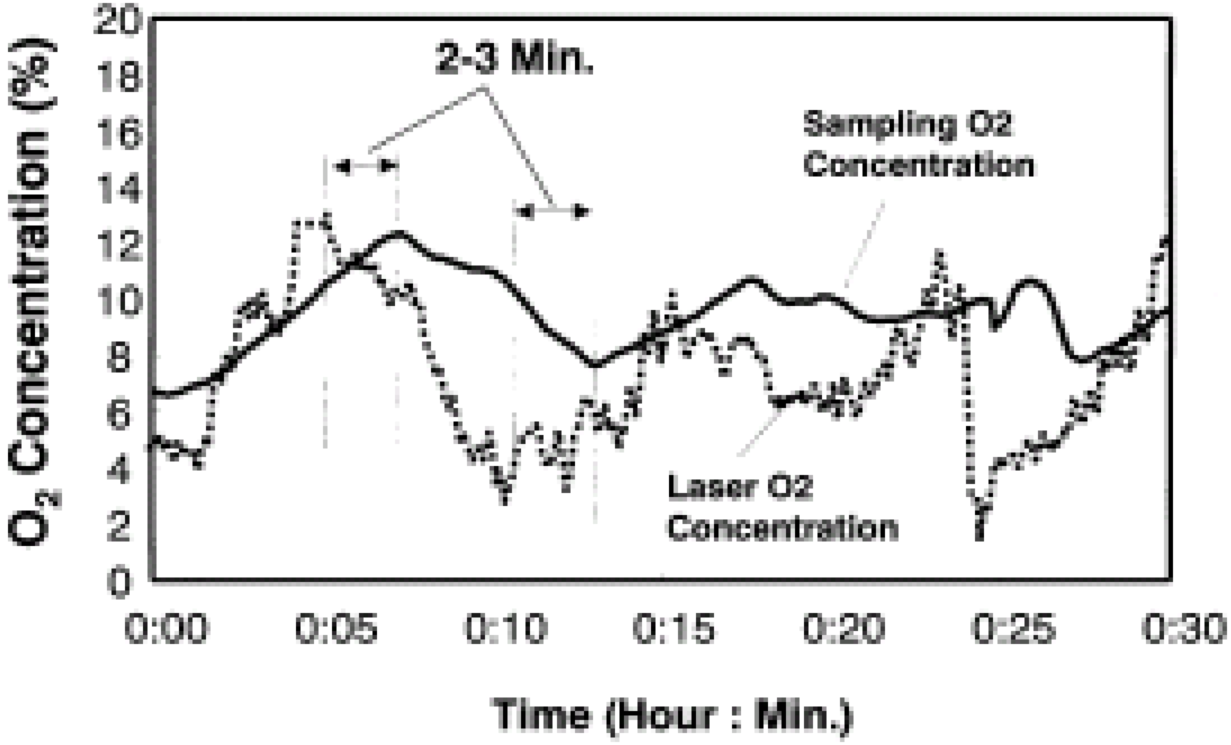
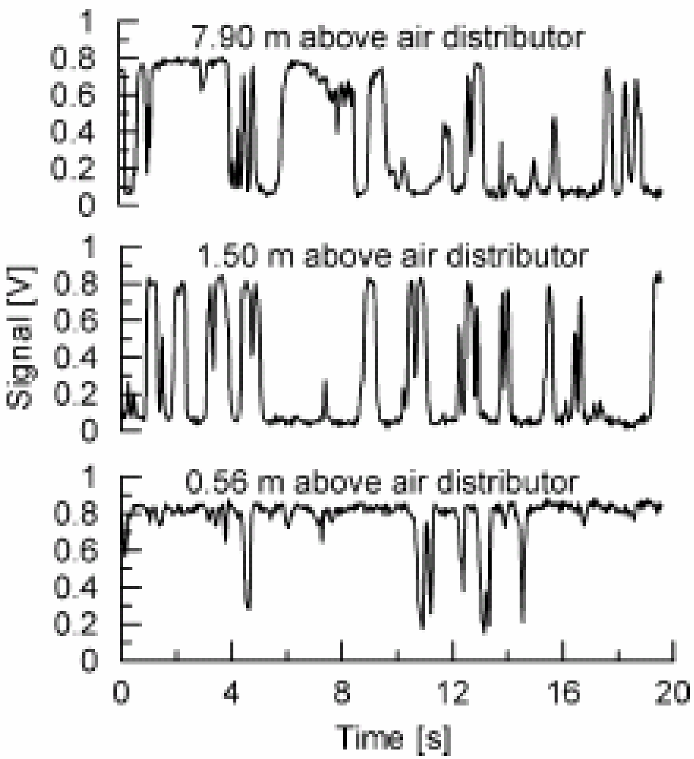
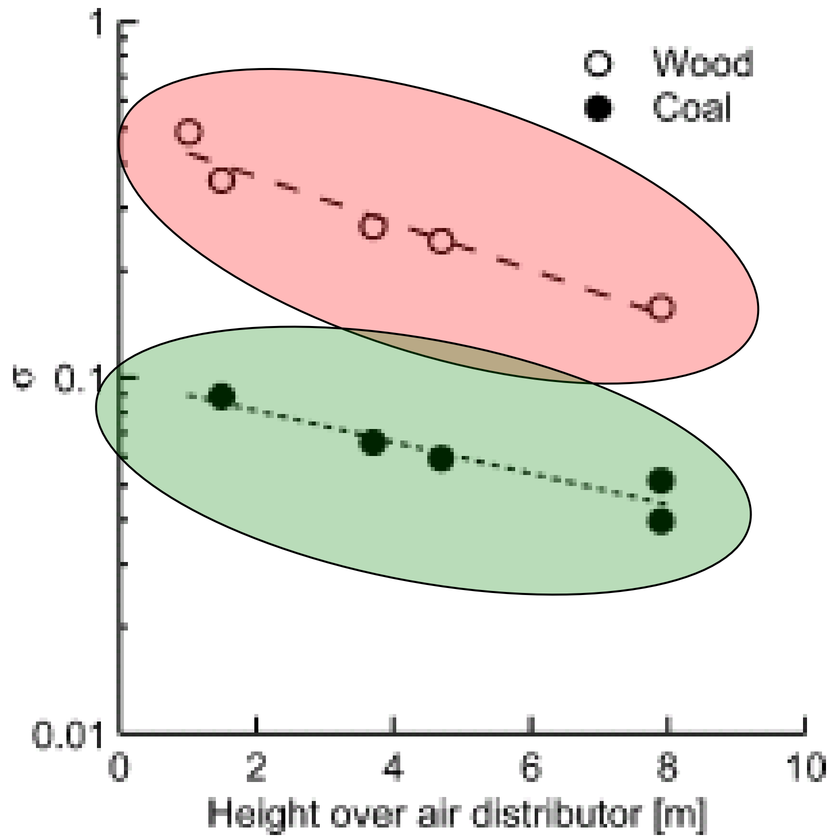


FIG. 6. O_2 measurement results.



7.90 m above air distributor
1.50 m above air distributor
0.56 m above air distributor
Signal [V]
Time [s]



Wood
Coal
σ
Height over air distributor [m]

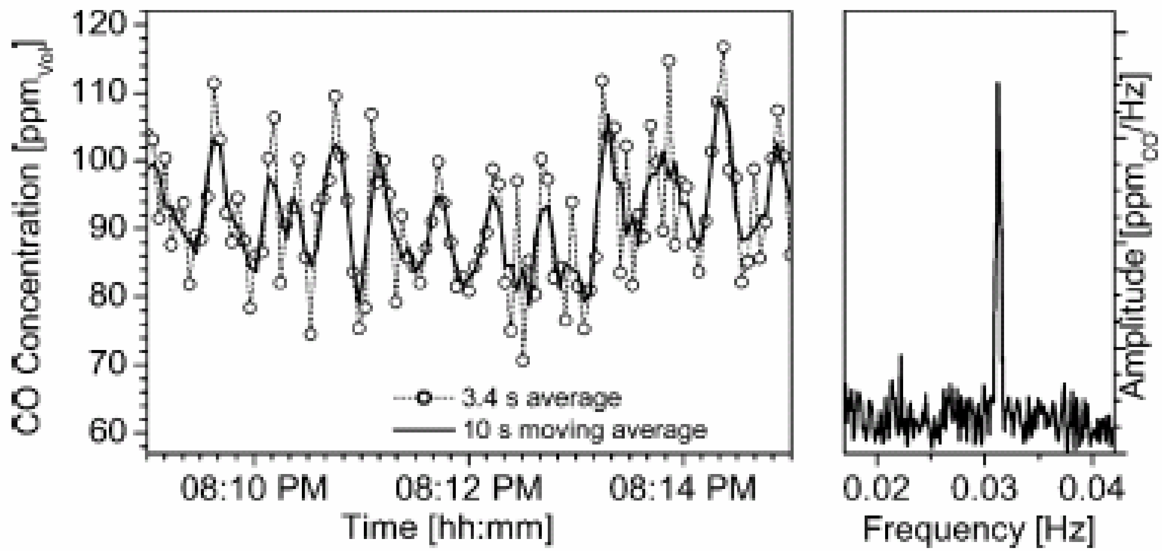
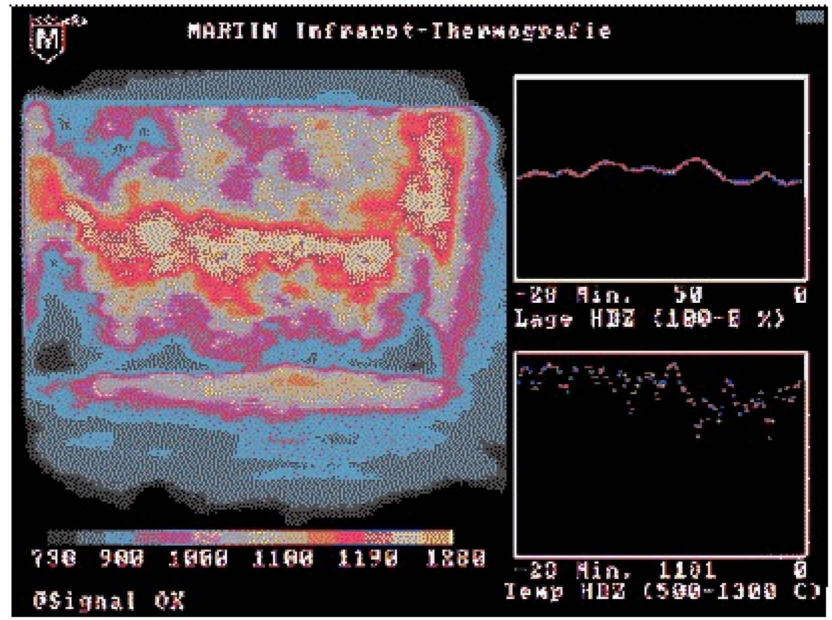


Fig. 7. Periodic CO fluctuations (left) with ±17 ppm amplitude (±10 ppm for 10 s average) measured at the RK exit. A FFT of the fluctuations (right) over a 2 h period shows same frequency as the feeding cycle of the incinerator.

Waste to Energy facility of BRESCIA

Expert system for flame analysis



- Fluctuations are likely to play a key role on emissions due to the inherent non-linearity of conversion pathways.

- Crucial effect of promoting effective mixing of heterogeneous and homogeneous phases and of promoting a proper level of turbulence.
This is accomplished by careful tailoring the time-temperature-oxidation history of the waste by proper space- and time-sensitive control of process parameters.

- Heterogenous combustion systems, unlike homogeneous combustion systems and burners of fine powders, are characterized by the impossibility of acting only on hydrodynamic aspects to control reaction conditions

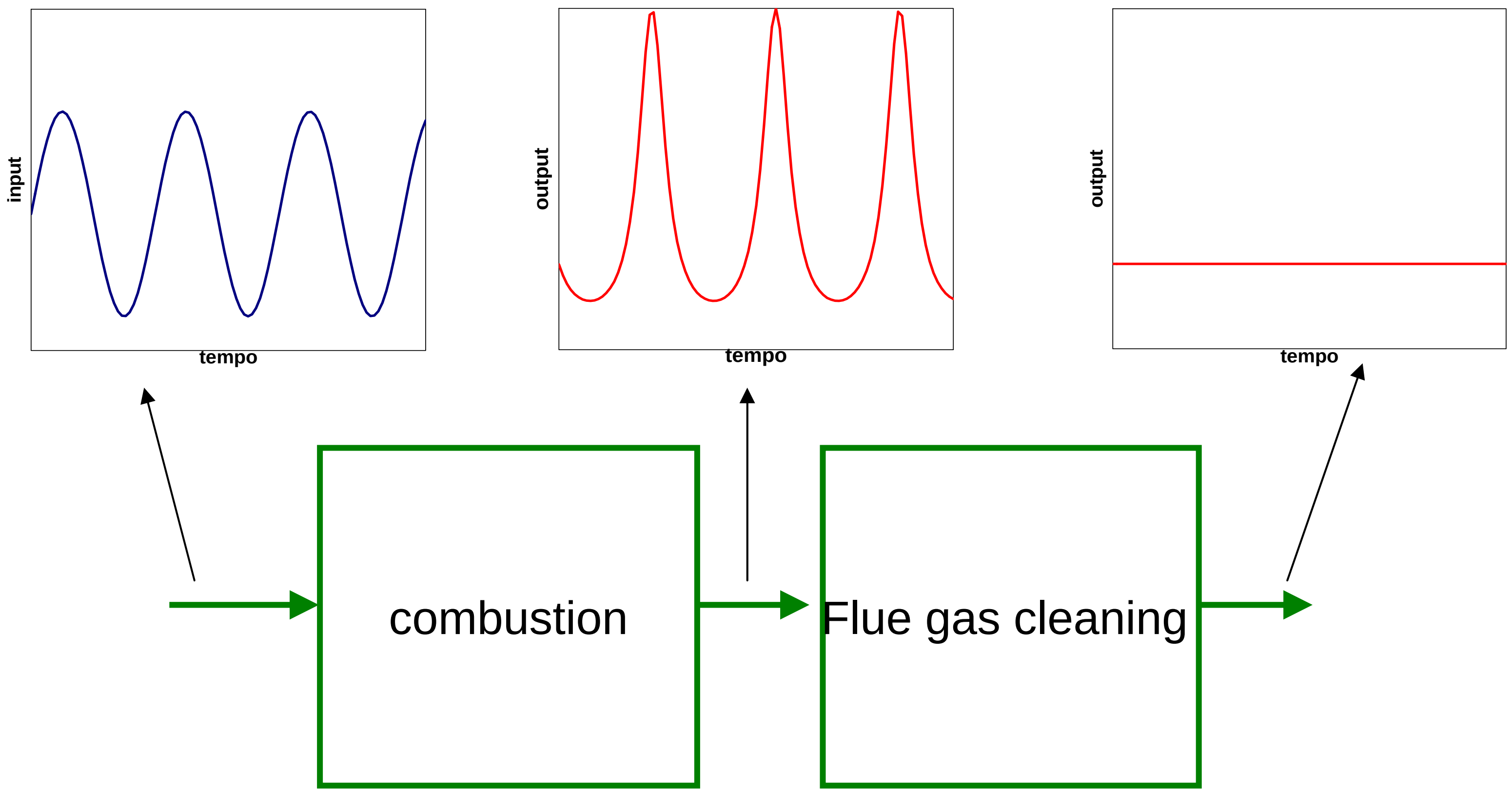
How can we handle uncertainty?

- **Advanced diagnostics techniques** able to highlight the levels of space-time variability of the operative parameters governing fuel conversion and in turn to activate appropriate feedback actions.

- **Adoption of an appropriate level of turbulence** on the basis of indications coming from the use of advanced CFD modeling and/or advanced diagnostics techniques

- **Adoption of the "carefulness principle"**: the adoption of appropriate means to moderate uncertainty and increase robustness with process upstream and/or downstream (back-up) actions.

direct combustion



Flue gas cleaning technologies used to control air pollution emission as an alternative route to accurate space- and time-sensitive control of process parameters.

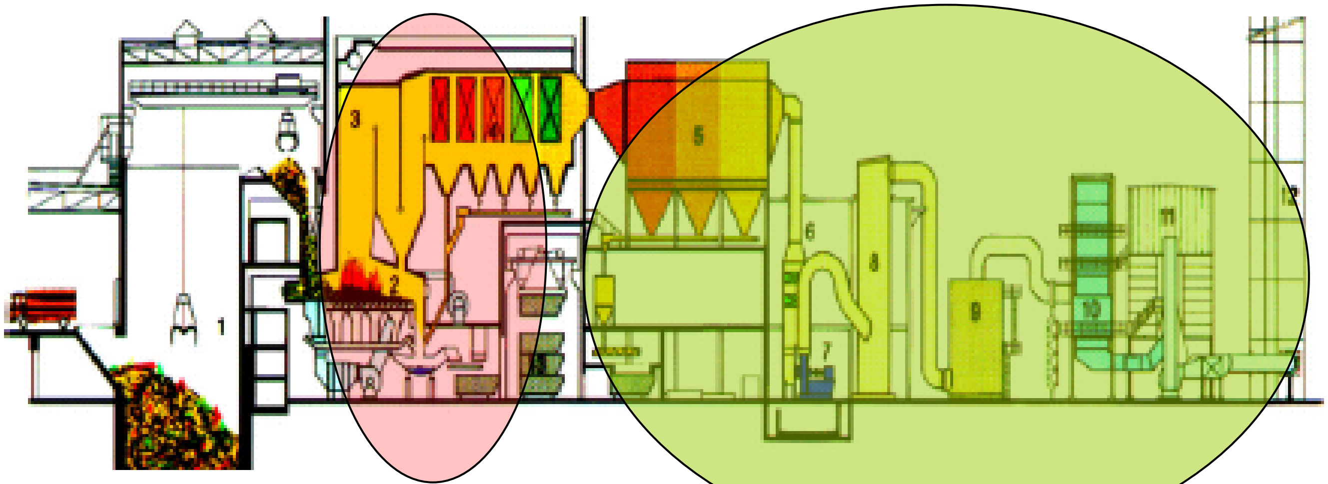
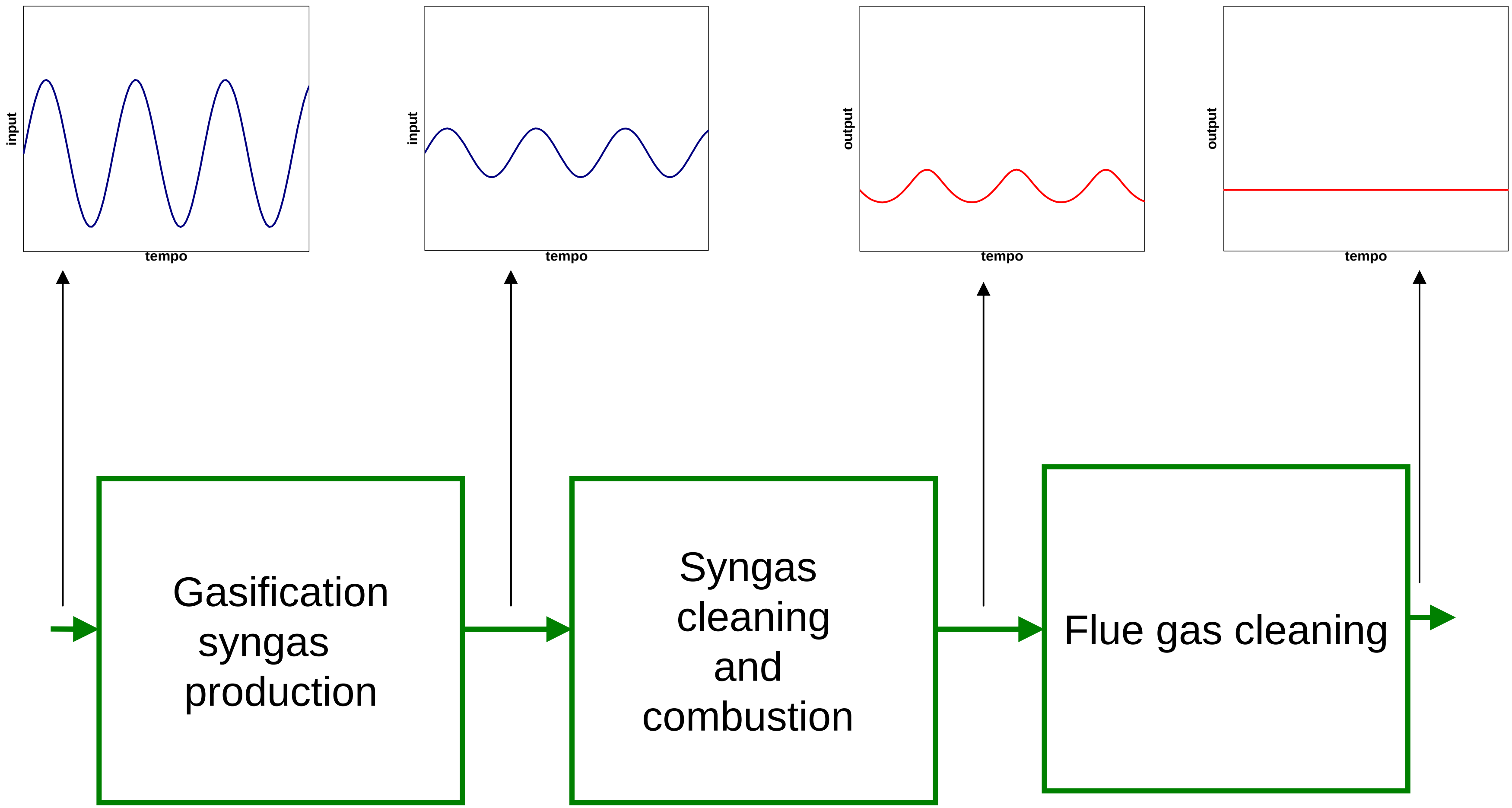


Fig. 2. Example of a state-of-the-art incineration plant (1, hopper; 2, furnace with grid; 3, after-burning chamber; 4, waste heat boiler; 5, electro static precipitator; 6, economizer; 7, blower; 8, scrubber; 9, wet electrostatic precipitator; 10, NO_x removal; 11, dioxin removal; 12, stack; and 13 slag removal, from [8]).

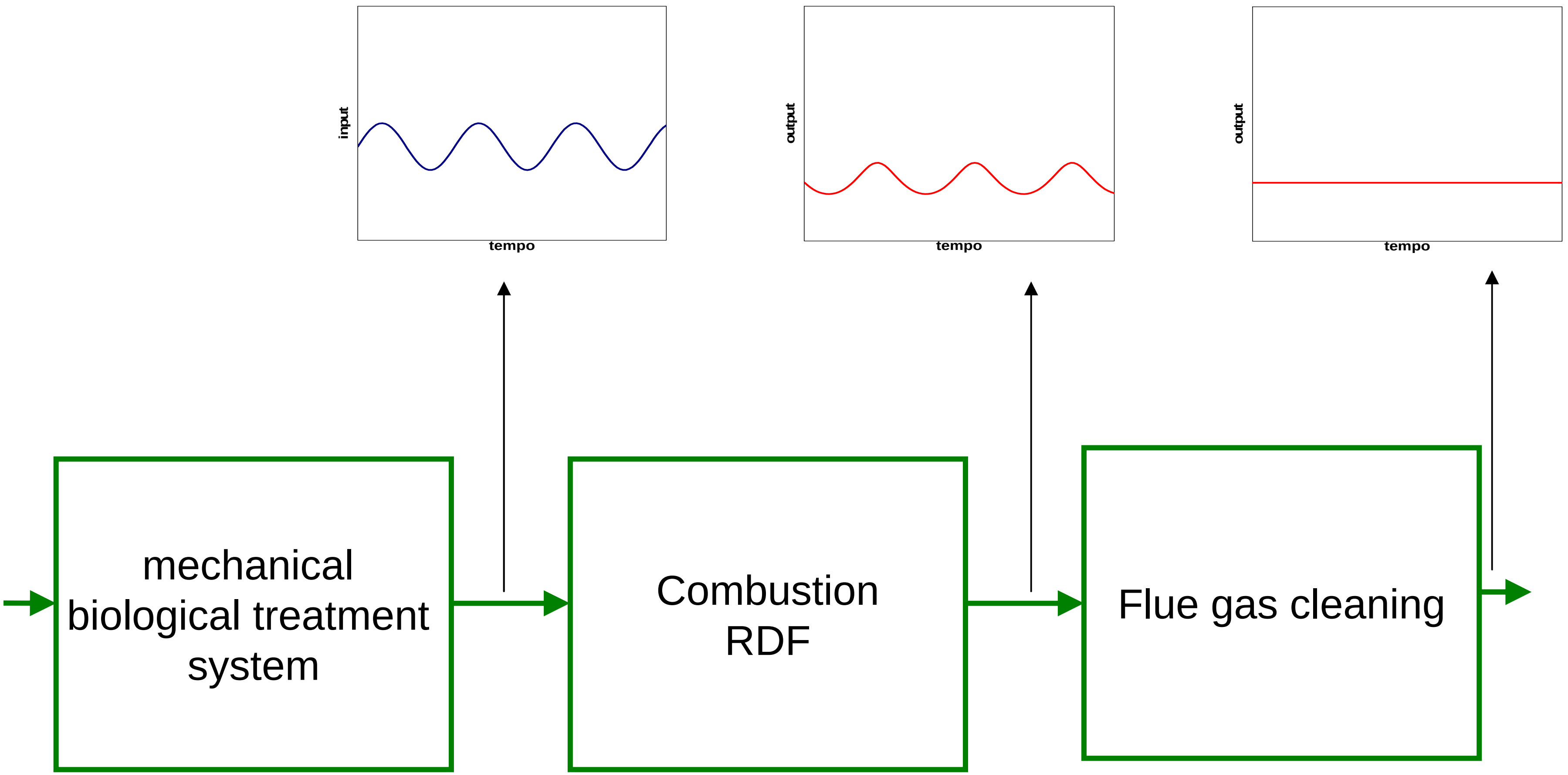
Combustion section

Flue gas cleaning section

Indirect combustion: gasification + syngas combustion



combustion of waste derived fuel



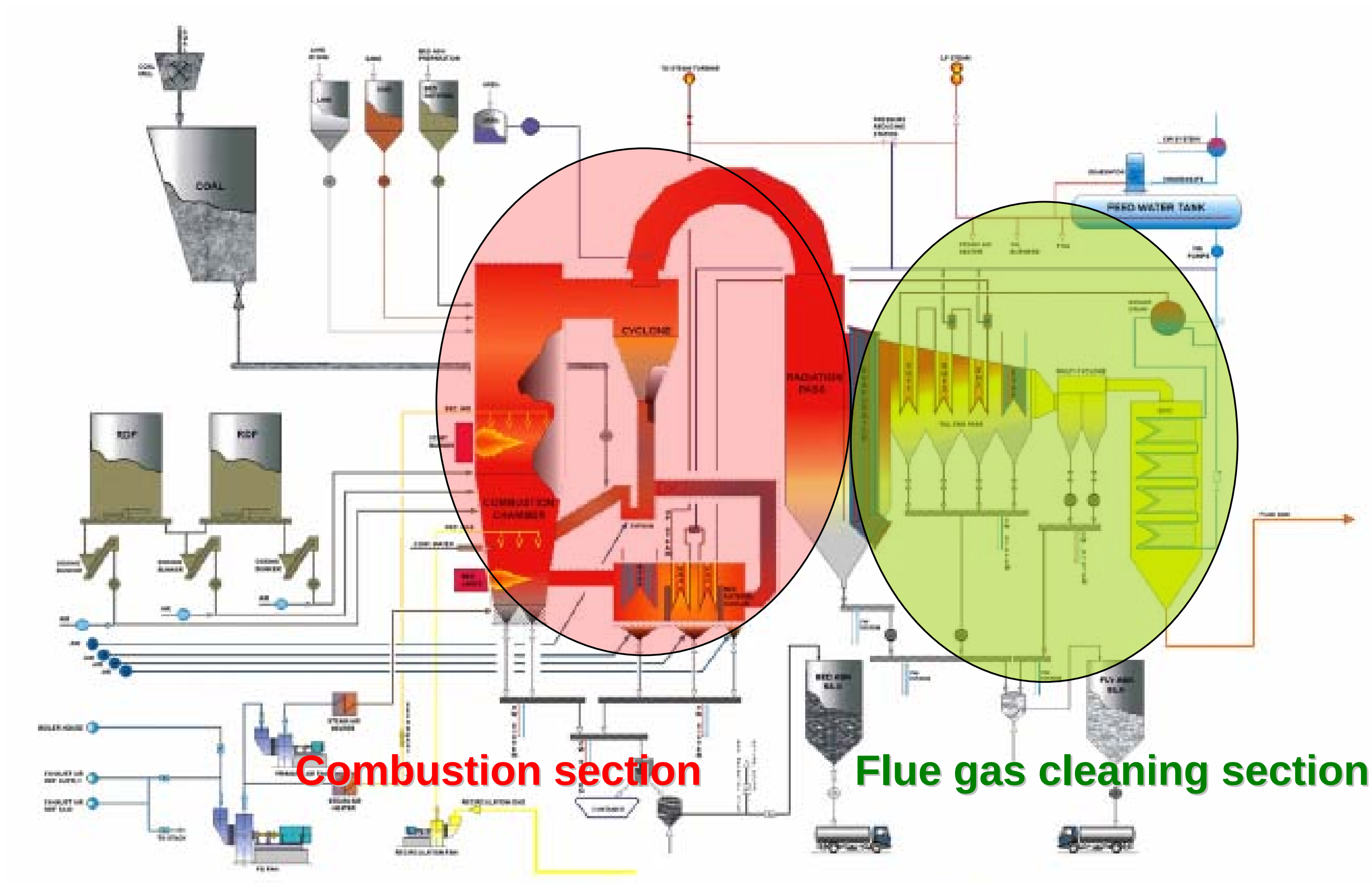
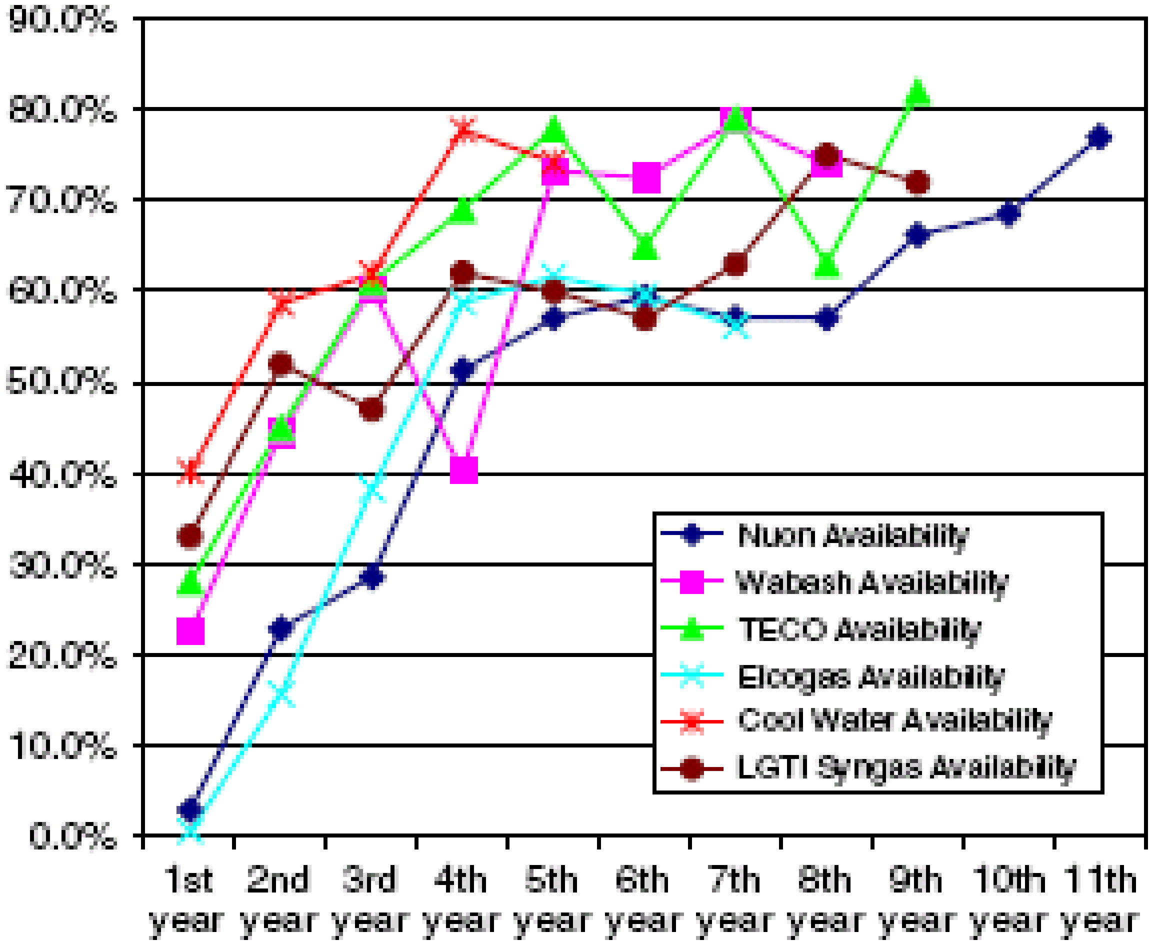


Fig. 9. The Neumünster boiler for preconditioned municipal waste [20].

Reliability
and the
“learning curve”

The "learning curve" of some Integrated Gasification Combined Cycle power plants



Set up of advanced waste disposal “knowledge-based” technologies

- advantages of “knowledge-based” technologies
  - reduces development and scale-up stages
  - promotes a faster acquirement of the learning curve. Moreover, the learning curves applies to different implementations of the technology
  - is the only one capable of ensuring effective technological "breakthrough"