POLITECNICO DI MILANO

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Alternative Strategies for Energy Recovery from Municipal Solid Waste

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Summary

1. Background
2. Alternative strategies and reference systems
3. Characterization of waste and RDF
4. System configuration
5. Methodology
6. Technologies
7. Energy balance
8. Emissions and environmental indicators
9. Costs
10. Conclusions

Summary

Disposal of MSW in Italy

1. Effort to reduce landfill use by enhancing material and energy recovery from waste
2. Material recovery has been given higher priority (although optimal role of material vs energy recovery has yet to be identified)
3. Energy recovery by combustion in WTE plants takes care of about 10% of total gross production
4. Endorsement of energy recovery through the production of an intermediate energy carrier: Refuse Derived Fuel
5. Recent years have witnessed an increasing production of RDF, even if only a fraction of it actually goes to energy recovery

Framework of this research

1. Since 2000, Federambiente (the federation of Italian municipal companies managing environmental services) has sponsored research at Politecnico di Milano to assess benefits and caveats of alternative strategies for energy recovery
2. First study on "dedicated" plants completed in 2002
3. Results on "non-dedicated" plants now being reviewed. Possible extension to account for additional data and experience being gathered in commercial installations with co-combustion of RDF and fossil fuel
4. Results given in this presentation will focus mainly on "dedicated" plants based on grate or fludized bed combustors (*Waste Management, 2005*)

Summary

Strategies

Processes and technologies for energy recovery from waste can be classified according to the sequence of operations whereby useful energy is produced.

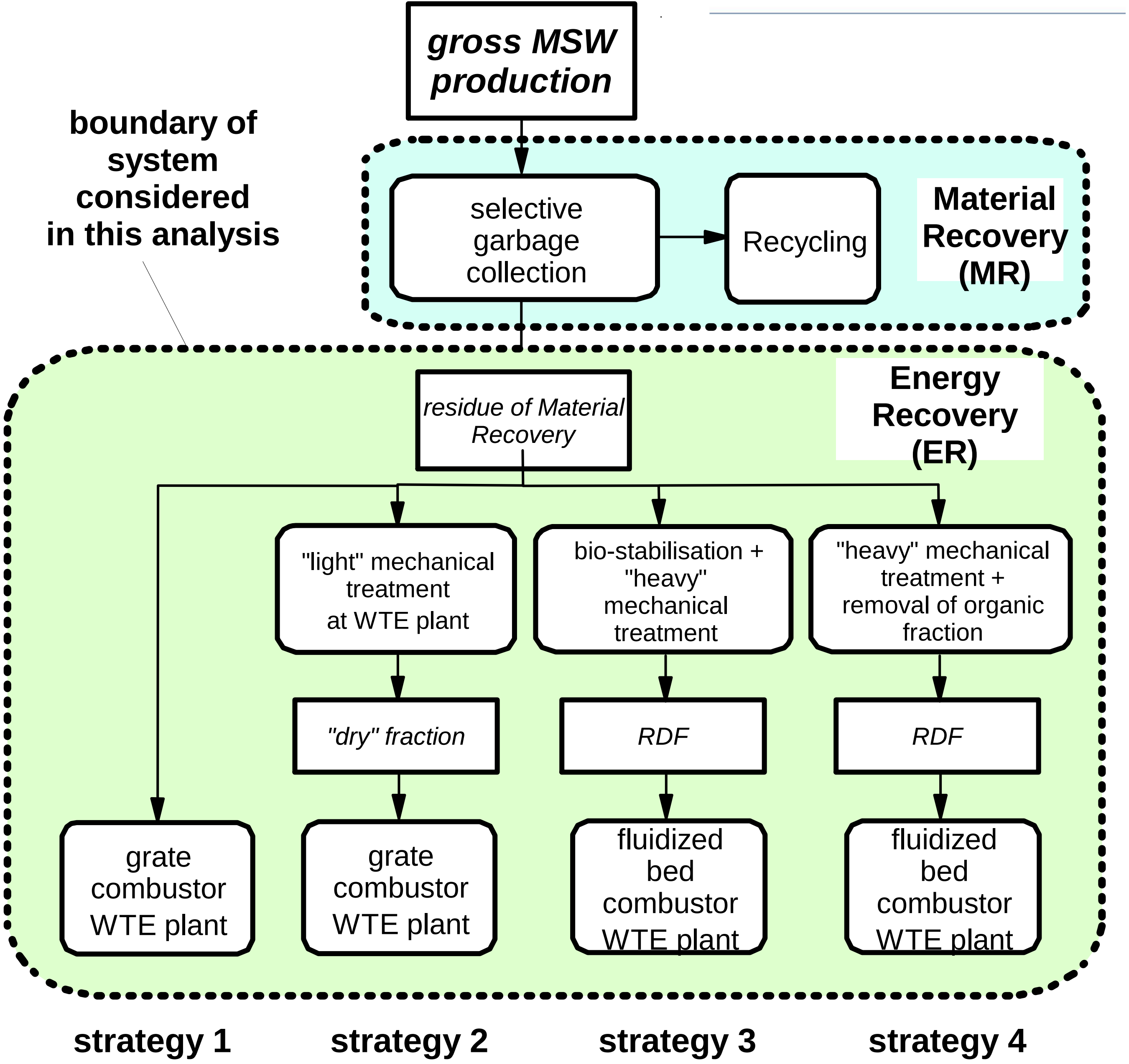
A) "Direct" recovery, where waste is used as the feedstock of a WTE plant to generate electricity and/or heat (or possibly commercial fuels)

B) "Indirect" recovery, where waste is first treated (mechanically and/or biologically) to generate an intermediate energy carrier called Refuse Derived Fuel (RDF). Subsequently, RDF can be used as the feedstock of:

- B1) "dedicated" plants designed and operated to handle only RDF
- B2) "non-dedicated" plants, where RDF is used together with other feedstocks, most likley fossil fuels (co-combustion)

Strategies

Systems with <u>dedicated</u> WTE plants considered in this analysis



boundary of system considered in this analysis

gross MSW production

selective garbage collection

Recycling

Material Recovery (MR)

residue of Material Recovery

Energy Recovery (ER)

"light" mechanical treatment at WTE plant

bio-stabilisation + "heavy" mechanical treatment

"heavy" mechanical treatment + removal of organic fraction

"dry" fraction

RDF

RDF

grate combustor WTE plant

grate combustor WTE plant

fluidized bed combustor WTE plant

fluidized bed combustor WTE plant

strategy 1

strategy 2

strategy 3

strategy 4

Reference systems

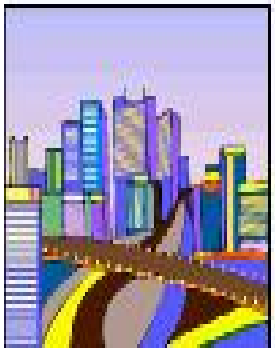
MSW production

"SMALL"

200.000 people

100.000 t/yr gross

65.000 t/yr downstream of selective garbage collection



"LARGE"

1.200.000 people

600.000 t/yr gross

390.000 t/yr downstream of selective garbage collection

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Residual Waste (RW)

Composition of residual waste (RW) downstream of 35% by weight selective garbage collection

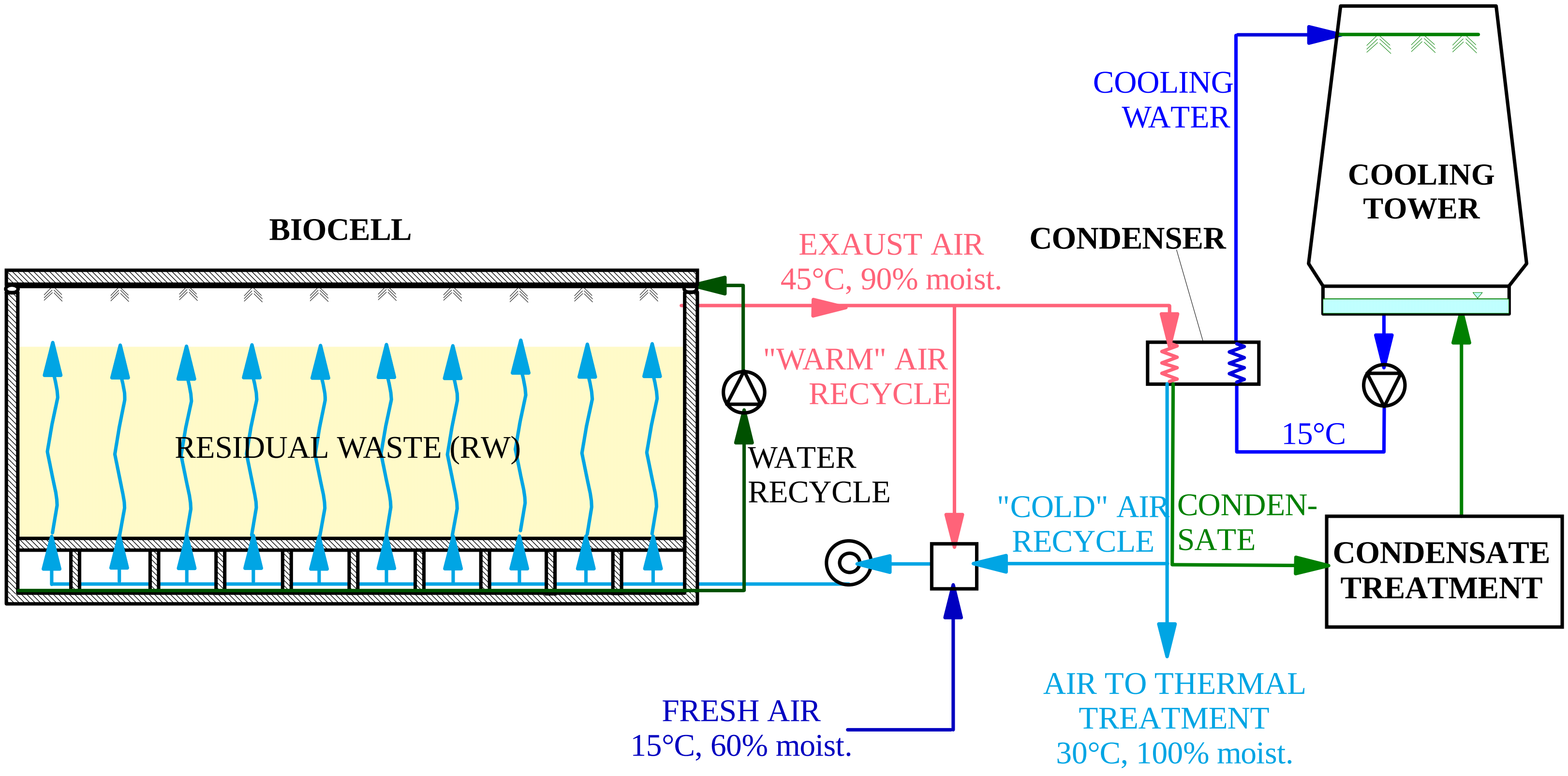
constituent	content in RW	composition			carbon content		LHV
		moisture	ash	volatile fraction	total	% renewable	
	% by weight						MJ/kg
paper & cardboard	24.5	14.0	5.0	81.0	37.6	100	13.22
wood	6.0	22.0	1.5	76.5	37.6	100	13.87
plastic	19.0	6.0	9.0	85.0	55.5	0	26.18
glass & inert material	3.5	2.5	95.0	2.5	1.0	0	-0.061
metals	3.5	5.0	92.5	2.5	1.0	0	-0.122
organic fraction	31.5	70.0	9.0	21.0	9.6	100	1.719
fines	12.0	30.0	35.0	35.0	20.5	60	4.395
Residual Waste	**100**	**31.8**	**16.6**	**51.6**	**27.6**	**16.0**	**10.11**

volatile fraction % by weight of total	
C	27.6
Cl	0.64
H	3.49
O	19.7
N	0.15
S	0.06
Total	**51.6**

Values in table are representative of Northern Italy conditions

Bio-drying

equivalent (time-averaged) steady-state mass and energy balances carried out by code developed at Dept. of Energy Engineering



configuration considered for RDF of strategy 3

Mechanical treatment

Each step modelled by matrix $[E]$ of separation efficiencies:

$$[\Gamma_{sep,i}] = [E_i]\cdot[\Gamma_{in,i}]$$

$$[\Gamma_{res,i}] = ([I] - [E_i])\cdot[\Gamma_{in,i}]$$

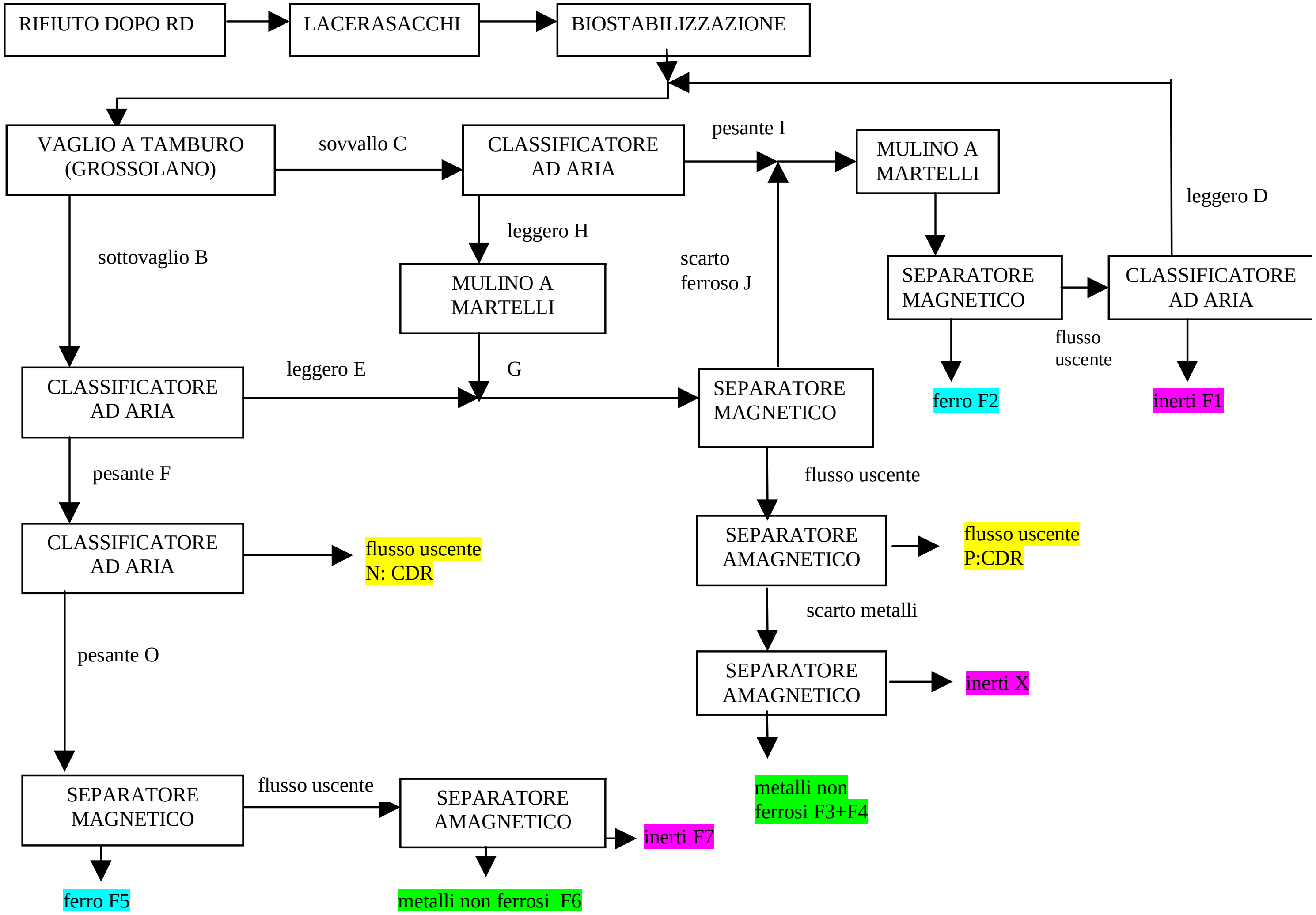
where:

n = number of fractions (paper, plastic, metals, etc.) considered
$[\Gamma_{in,i}]$ = n×1 vector of mass fractions of flow entering step i
$[\Gamma_{sep,i}]$ = n×1 vector of mass fractions of flow separated at step i
$[\Gamma_{res,i}]$ = n×1 vector of mass fractions of residue of step i
$[E_i]$ = n×n diagonal matrix of separation efficiencies of step i
$[I]$ = n×n diagonal identity matrix

$[E_i]$ is assumed constant, although in pratice there is some dependence on $[\Gamma_{in,i}]$. Its value based on literature data, calibrated to match final RDF composition.

Mechanical treatment

Configuration considered for RDF of strategy 3



RIFIUTO DOPO RD

LACERASACCHI

BIOSTABILIZZAZIONE

VAGLIO A TAMBURO (GROSSOLANO)

sovvallo C

CLASSIFICATORE AD ARIA

pesante I

MULINO A MARTELLI

leggero D

leggero H

sottovaglio B

MULINO A MARTELLI

scarto ferroso J

SEPARATORE MAGNETICO

CLASSIFICATORE AD ARIA

flusso uscente

ferro F2

inerti F1

CLASSIFICATORE AD ARIA

leggero E

G

SEPARATORE MAGNETICO

pesante F

flusso uscente

CLASSIFICATORE AD ARIA

flusso uscente N: CDR

SEPARATORE AMAGNETICO

flusso uscente P:CDR

scarto metalli

pesante O

SEPARATORE AMAGNETICO

inerti X

metalli non ferrosi F3+F4

SEPARATORE MAGNETICO

flusso uscente

SEPARATORE AMAGNETICO

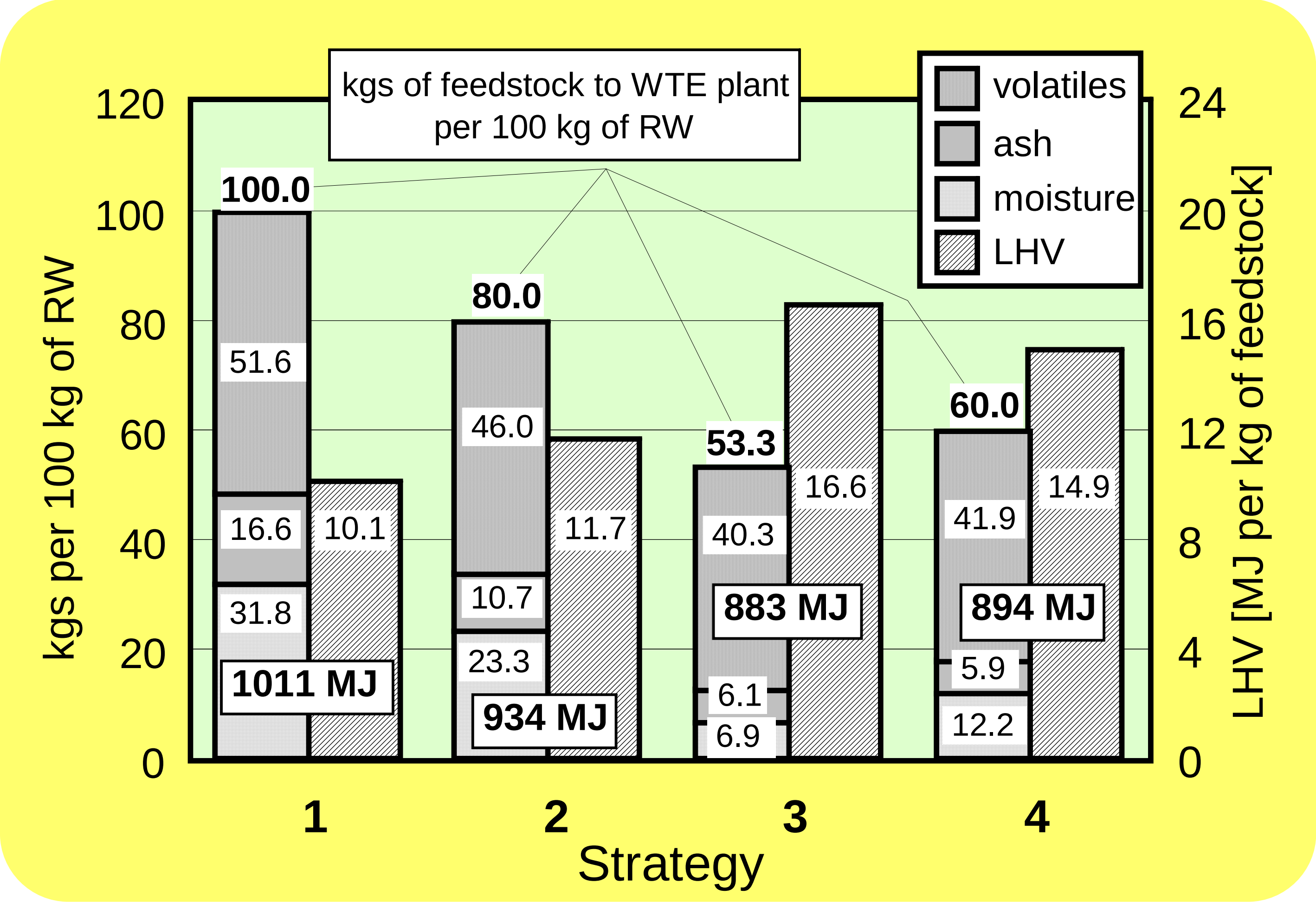
inerti F7

ferro F5

metalli non ferrosi F6

RDF properties

Models of mechanical treatment and bio-drying (where applicable) allow calculating RDF composition and heating value

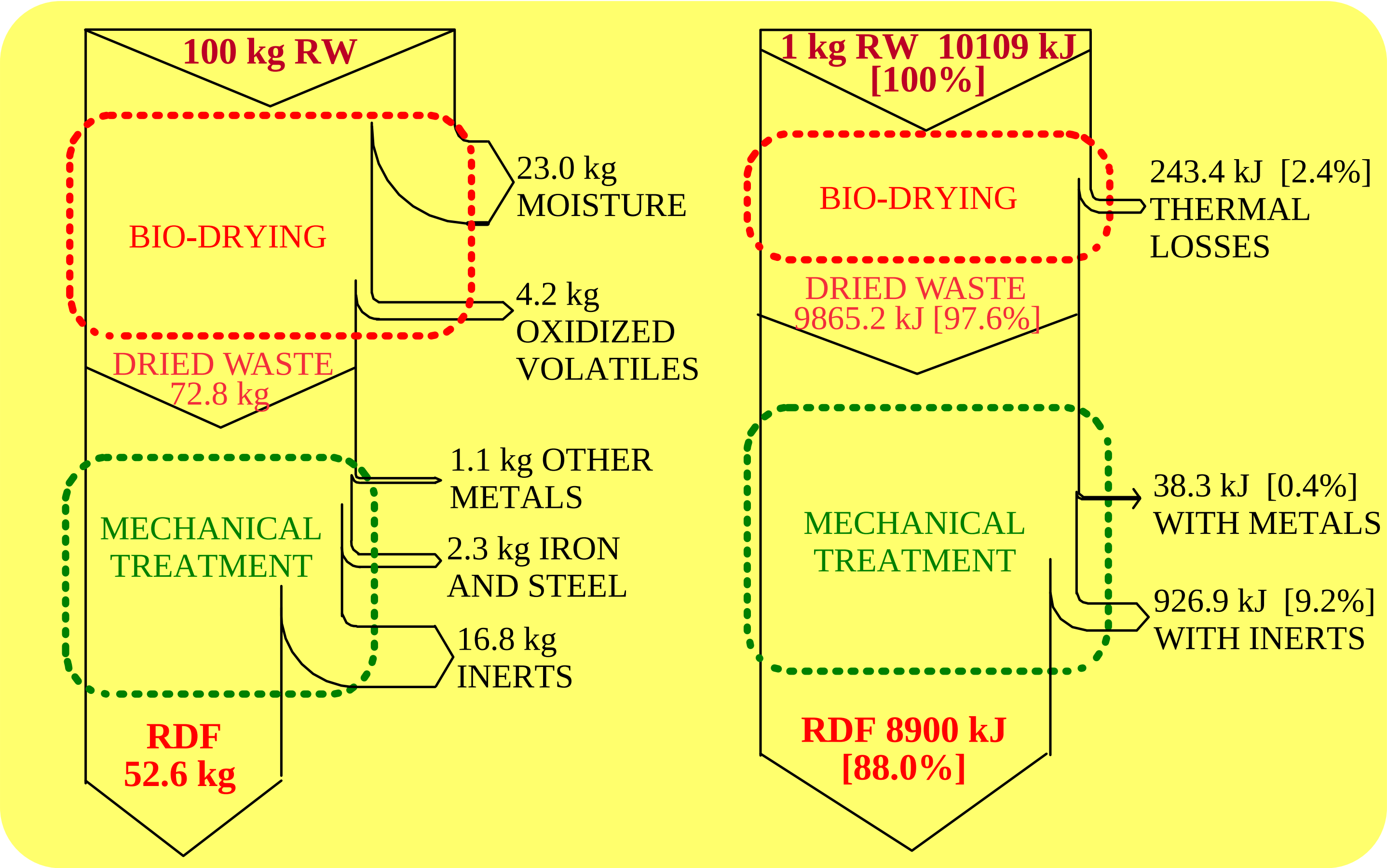


RDF production

Mass and energy balance for the RDF of Strategy 3, updated with recent data on RW composition, bio-drying and mechanical treatment

Mass

Energy (LHV)



100 kg RW

BIO-DRYING

23.0 kg
MOISTURE

4.2 kg
OXIDIZED
VOLATILES

DRIED WASTE
72.8 kg

MECHANICAL
TREATMENT

1.1 kg OTHER
METALS

2.3 kg IRON
AND STEEL

16.8 kg
INERTS

RDF
52.6 kg

1 kg RW 10109 kJ
[100%]

BIO-DRYING

243.4 kJ [2.4%]
THERMAL
LOSSES

DRIED WASTE
9865.2 kJ [97.6%]

MECHANICAL
TREATMENT

38.3 kJ [0.4%]
WITH METALS

926.9 kJ [9.2%]
WITH INERTS

RDF 8900 kJ
[88.0%]

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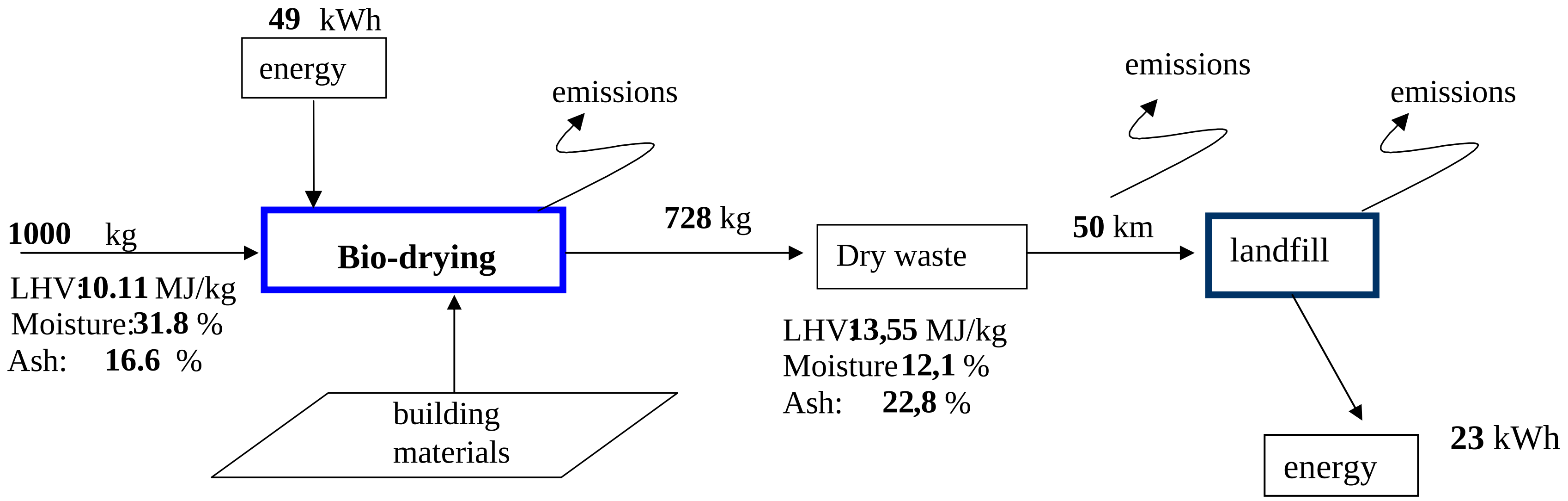
System configuration

Strategy 0: bio-drying + landfill

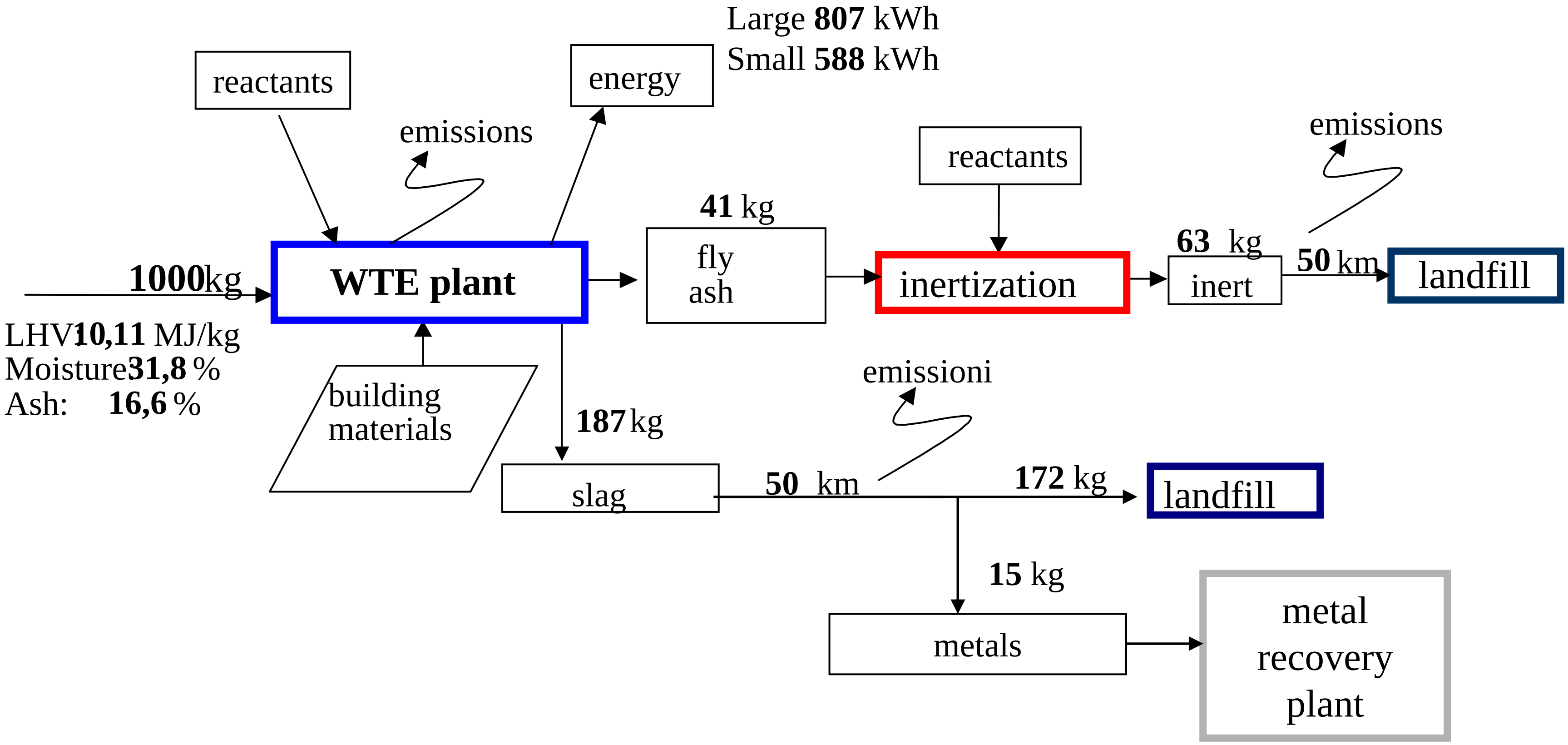


49 kWh
energy
emissions
1000 kg
LHV: **10.11** MJ/kg
Moisture: **31.8** %
Ash: **16.6** %
Bio-drying
building materials
728 kg
Dry waste
LHV: **13,55** MJ/kg
Moisture **12,1** %
Ash: **22,8** %
emissions
50 km
landfill
emissions
23 kWh
energy

- bio-drying carried out on the whole mass of Residual Waste (RW)
- biogas from landfill feeds internal combustion engines

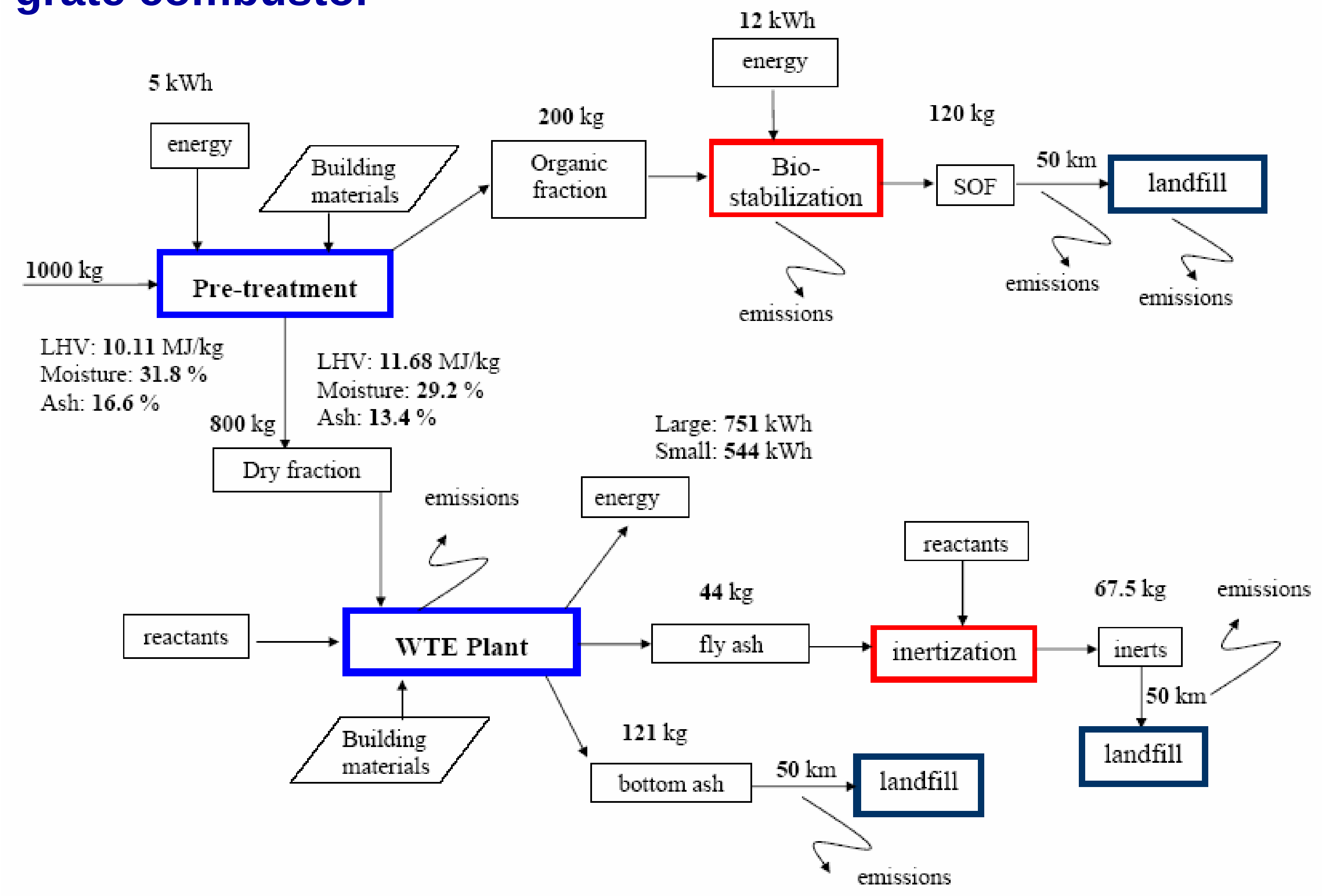
System configuration

Strategy 1: Residual Waste fed directly to a dedicated WTE plant with grate combustor



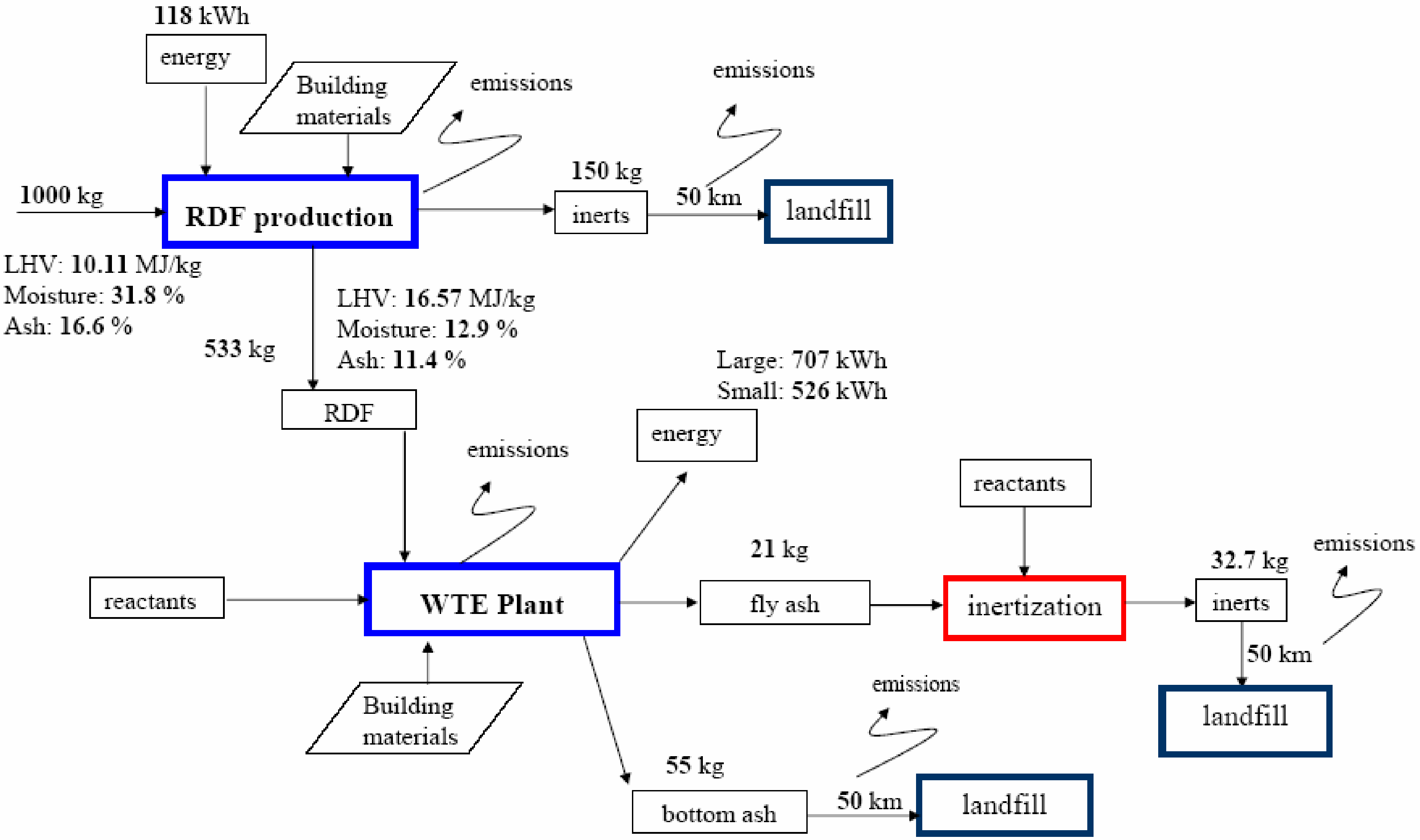
System configuration

Strategy 2: "light" treatment of RW at a dedicated WTE plant with grate combustor



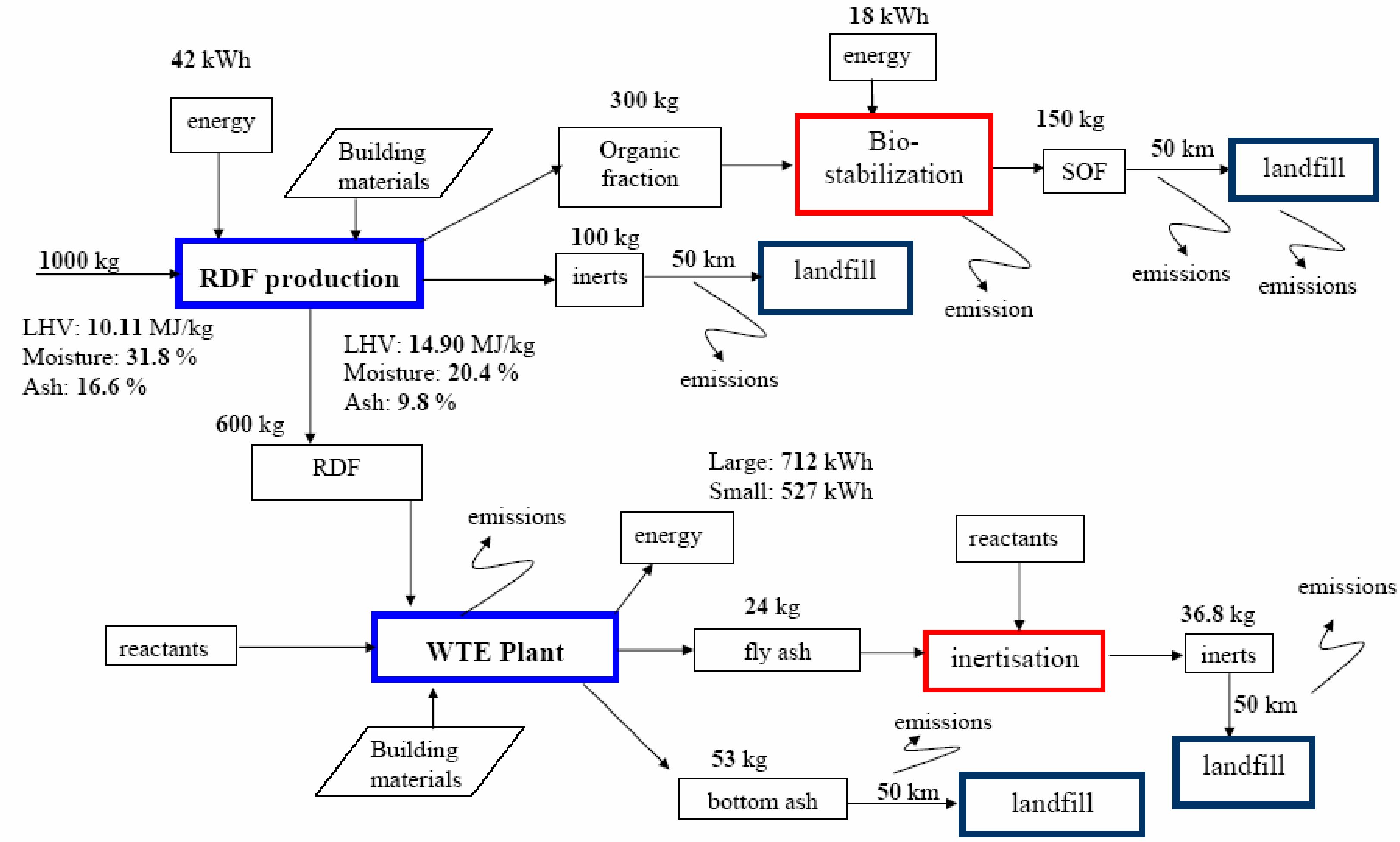
System configuration

Strategy 3: produce RDF by bio-drying ahead of mechanical treatment, then feed RDF into a dedicated WTE plant with fludized bed combustor



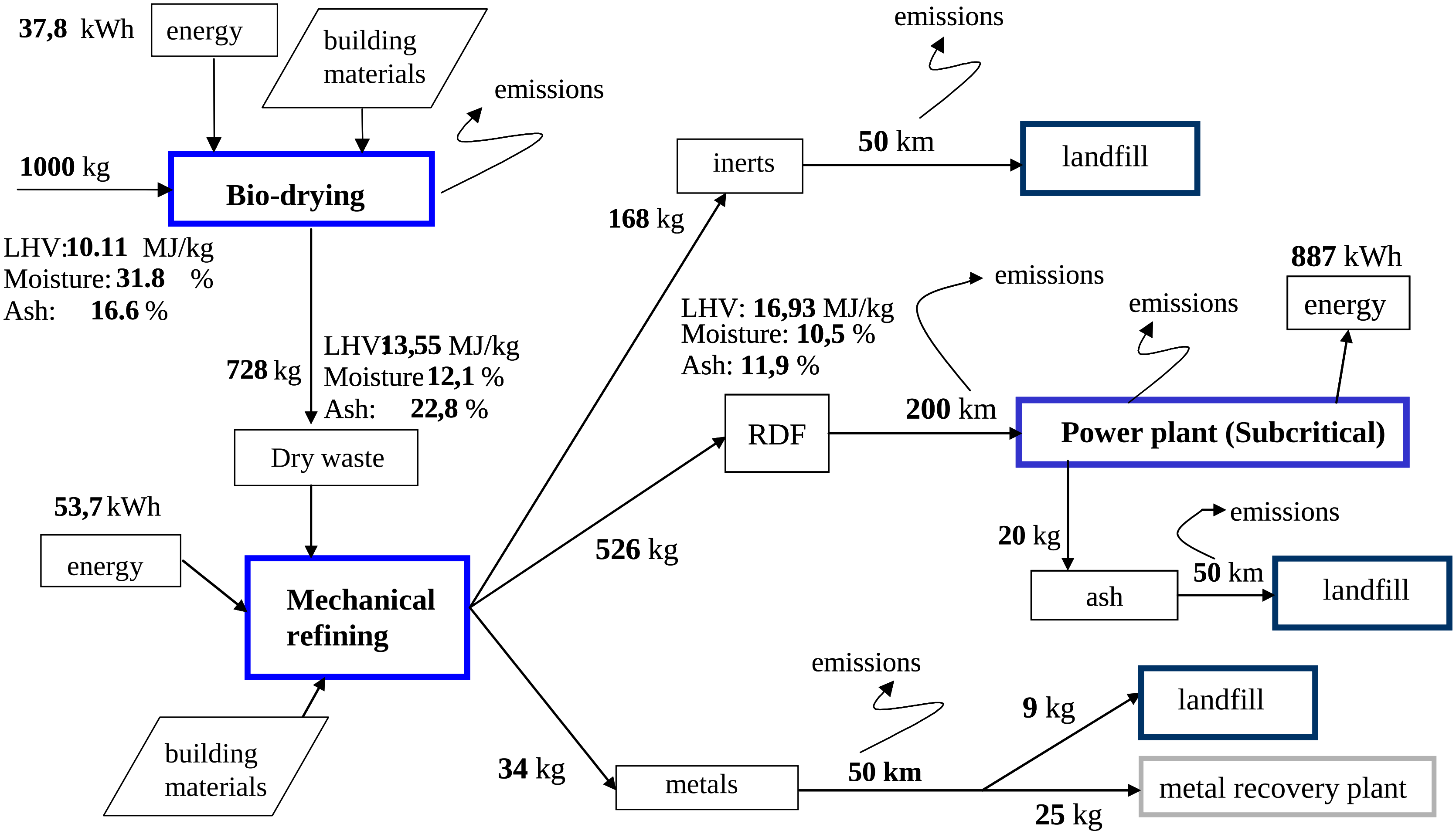
System configuration

Strategy 4: produce RDF by <u>first removing the organic fraction</u> (to be bio-dryed), then feed RDF into a <u>dedicated</u> WTE plant with fludized bed combustor



System configuration

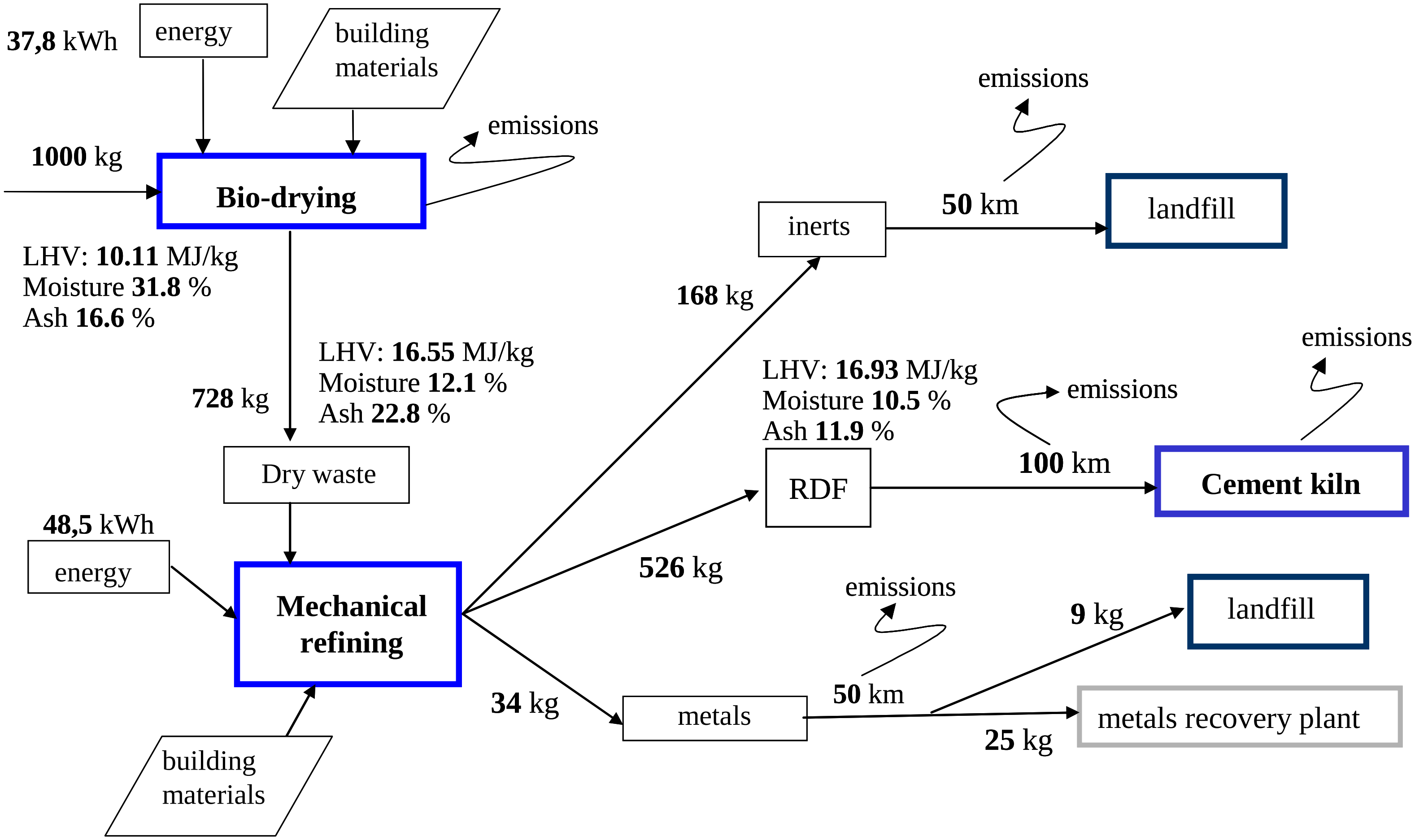
Strategy 5: produce RDF as in strategy 3 and then feed it into a non-dedicated fossil-fuel-fired power station



37,8 kWh
energy
building materials
emissions
1000 kg
Bio-drying
LHV:**10.11** MJ/kg
Moisture: **31.8** %
Ash: **16.6** %
728 kg
LHV**13,55** MJ/kg
Moisture **12,1** %
Ash: **22,8** %
Dry waste
53,7 kWh
energy
Mechanical refining
building materials
168 kg
inerts
50 km
emissions
landfill
526 kg
LHV: **16,93** MJ/kg
Moisture: **10,5** %
Ash: **11,9** %
RDF
200 km
emissions
Power plant (Subcritical)
emissions
887 kWh
energy
20 kg
ash
50 km
emissions
landfill
34 kg
metals
50 km
emissions
9 kg
landfill
25 kg
metal recovery plant

System configuration

Strategy 6: produce RDF as in strategy 3 and then feed it into a non-dedicated cement kiln

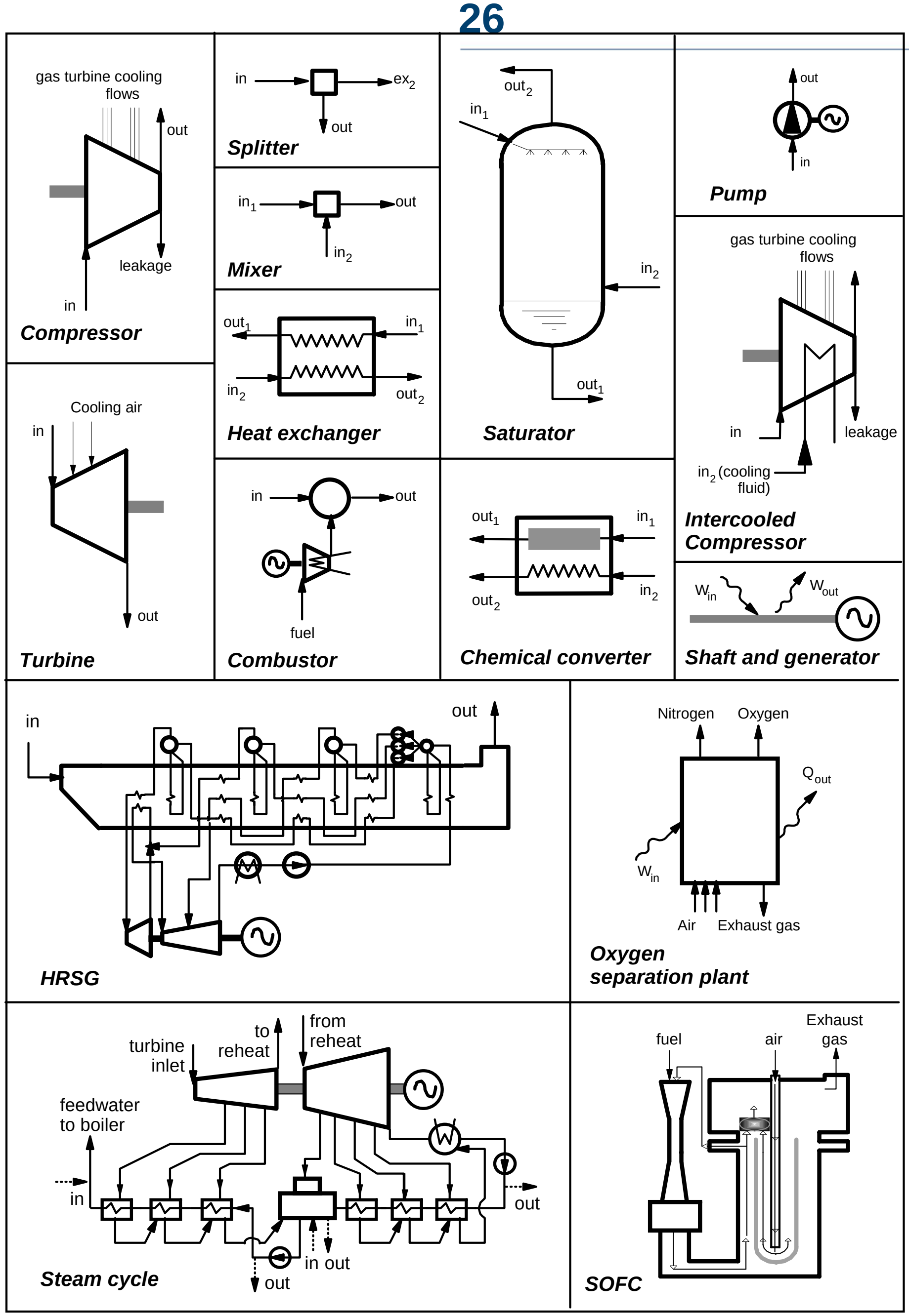


Summary

Modelization of WTE plant

Energy and mass balances have been evaluated by a modular computer code developed at Politecnico di Milano.

System is defined as an ensemble of basic components, with characteristics and interconnections defined by user.



Environmental Impact Indicators

The environmental balance has been carried out by a LCA approach, taking into consideration all direct and indirect atmospheric emissions.

LCA was based on the CML Guidelines. The SimaPro5® commercial software was utilised for the final calculations of the emission inventory and of the four major impact indicators:

- ➢ Global Warming Potential (GWP – kgCO_2 eq.)
- ➢ Human Toxicity Potential (HTTP – kg 1,4-DCB eq.)
- ➢ Acidification Potential (AP – kgSO_2 eq.)
- ➢ Photochemical Ozone Creation Potential (POCP – kgC_2H_4 eq.)

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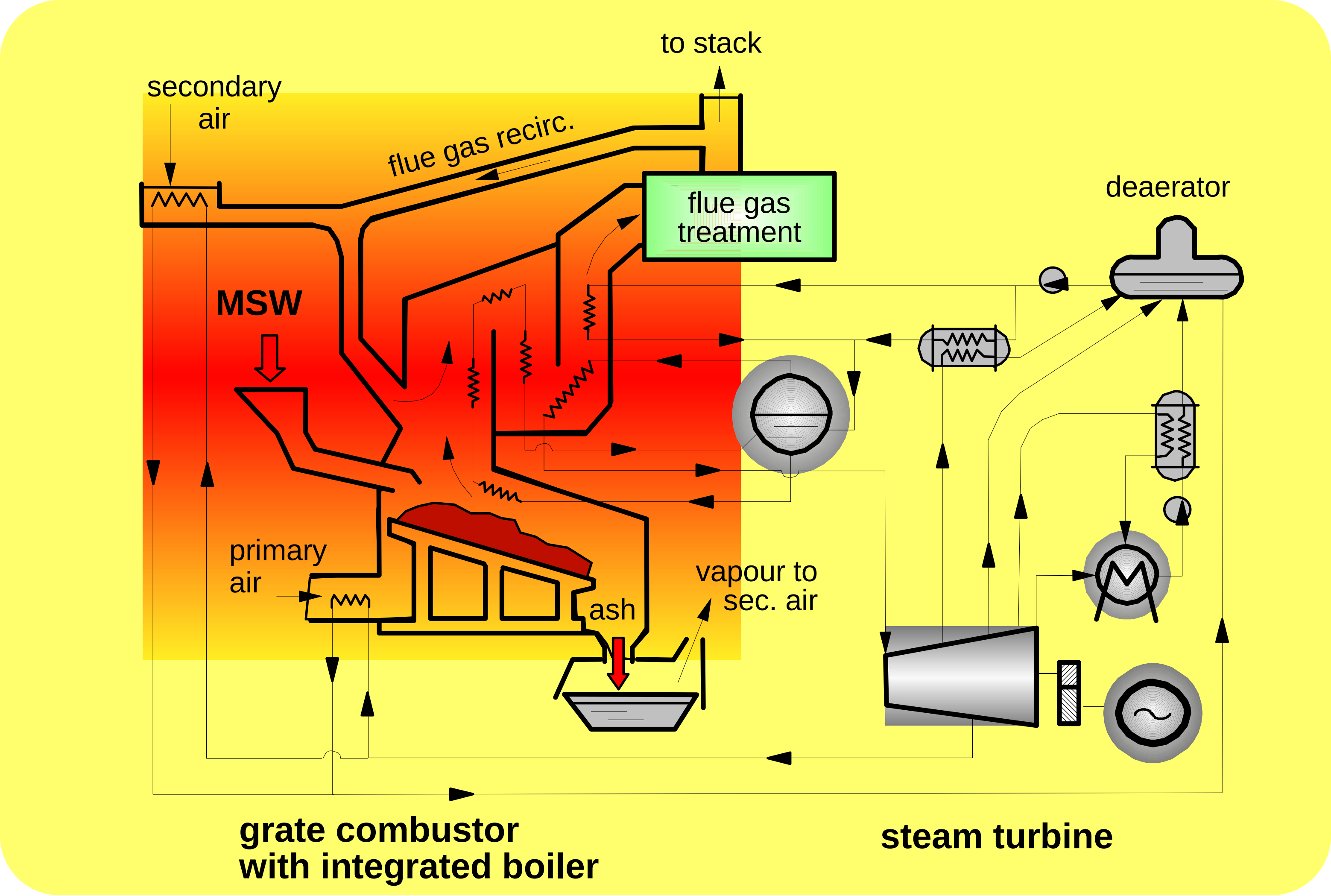
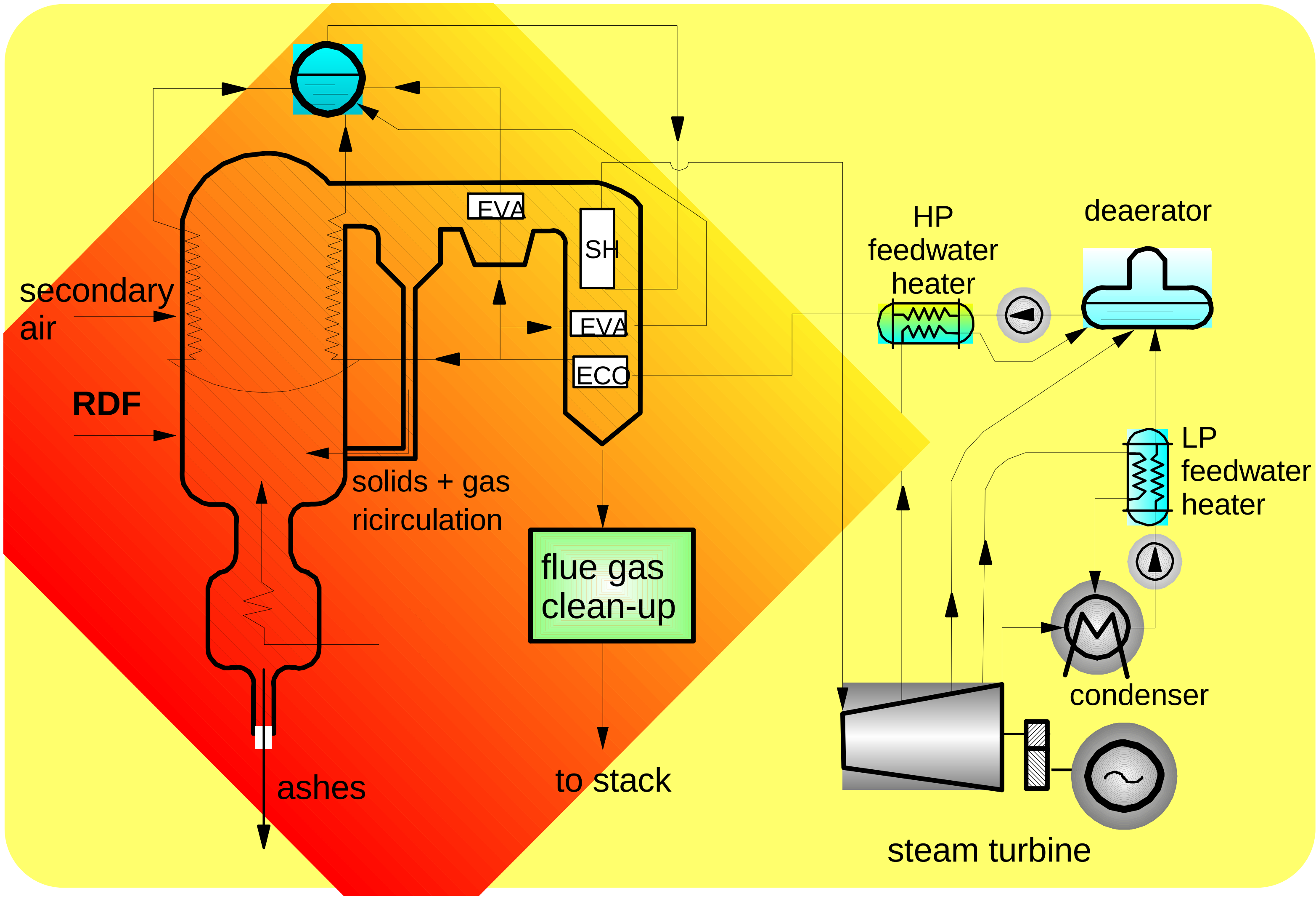
Grate combustor

Air-cooled grate, integrated boiler, Rankine steam cycle, dry flue gas treatment with bag filter



Fluidized bed combustor

Circulating bed, integrated boiler, Rankine steam cycle, dry flue gas treatment with bag filter



Steam cycle

design parameter	**unit**	**plant size**	
		small	large
evaporation pressure	*bar*	45	65
extraction for air pre-heating(1)		2.6	
deaerator pressure		2.0	
condensation pressure		0.08	0.06
gas temperature at SH inlet	*°C*	max 650(2)	
steam temperature at SH outlet		400	440
gas temperature at ECO outlet		160	140
temperature of primary air		120	
temperature of secondary air		120	
LP feedwater heaters ahead of deaerator		1	2
MP feedwater heaters		none	
flue gas recirculated	*% mass*	15	
flue gas oxygen content	*% volume*	6.0	5.0
loss due to unburnt carbon(3)	*% LHV*	0.8	

Performances of WTE plants

System size		Small				Large					
Gross MSW production	t/yr	100,000				600,000					
Residual Waste (RW)	t/yr	65,000				390,000					
Strategy		1	2	3	4	1			2	3	4
WTE plant output		electricity				electr.	cog A	cog B	electricity		
Feedstock to WTE plant	MJ_{LHV}/kg	10.11	11.68	16.57	14.90	10.11			11.68	16.57	14.90
	t/yr	65,000	51,977	34,635	38,977	390,000			311,864	207,807	233,864
	MW_{LHV}	25.4	23.4	22.2	22.4	152.1			140.5	132.9	134.5
Steam flow to turbine	kg/s	8,70	8,08	7,63	7,70	51,87			48,18	44,97	45,41
Gas flow (dry, 11% O_2)	m_n^3/s	15.55	13.84	12.06	12.58	91.93			81.91	71.69	74.63
Dry ashes in feedstock	t/yr	10,805	6,940	3,951	3,822	64,828			41,639	23,706	22,932
Inert matrls to landfill		16,835	11,570	5,720	5,850	101,010			69,420	34,320	35,100
Gross electric power	MWel	6,68	6,17	5,95	6,01	49,26	42,94	36,48	45,64	43,58	44,03
Net electric power	**MWel**	**5.31**	**4.91**	**4.75**	**4.76**	**43.73**	**37.84**	**31.81**	**40.66**	**38.32**	**38.56**
Net LHV efficiency	**%**	**20.9**	**21.0**	**21.4**	**21.2**	**28.8**	**24.9**	**20.9**	**28.9**	**28.8**	**28.7**
kWh per t of feedstock		**588**	**680**	**987**	**879**	**807**	**699**	**587**	**938**	**1,327**	**1,186**
kWh per t of RW			**544**	**526**	**527**				**751**	**707**	**712**
Useful thermal power	MWth						34.4	68.8			
MJ_{th} per t of feedstock							2287	4574			
MJ_{th} per t of RW											

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Overall energy balance

1. Account for emissions from transport
2. Account for avoided emissions of electricity (and heat) production
3. Convert all values to Tons of Oil Equivalent (TOE)

Power Generation	
technology	steam cycle
primary energy (LHV)	50% heavy oil + 50% nat gas
average net efficiency	37.5 % (LHV)
kgOE per MWh_{el}	229.3
Transport of solid residues	
average distance	50 km
diesel fuel consumption	0.051 kgOE/t-km
District heating (only for cogen cases)	
thermal losses	19% of heat input
eff. of displaced boilers	80%
Total energy use	
3.2 TOE per yr per capita	

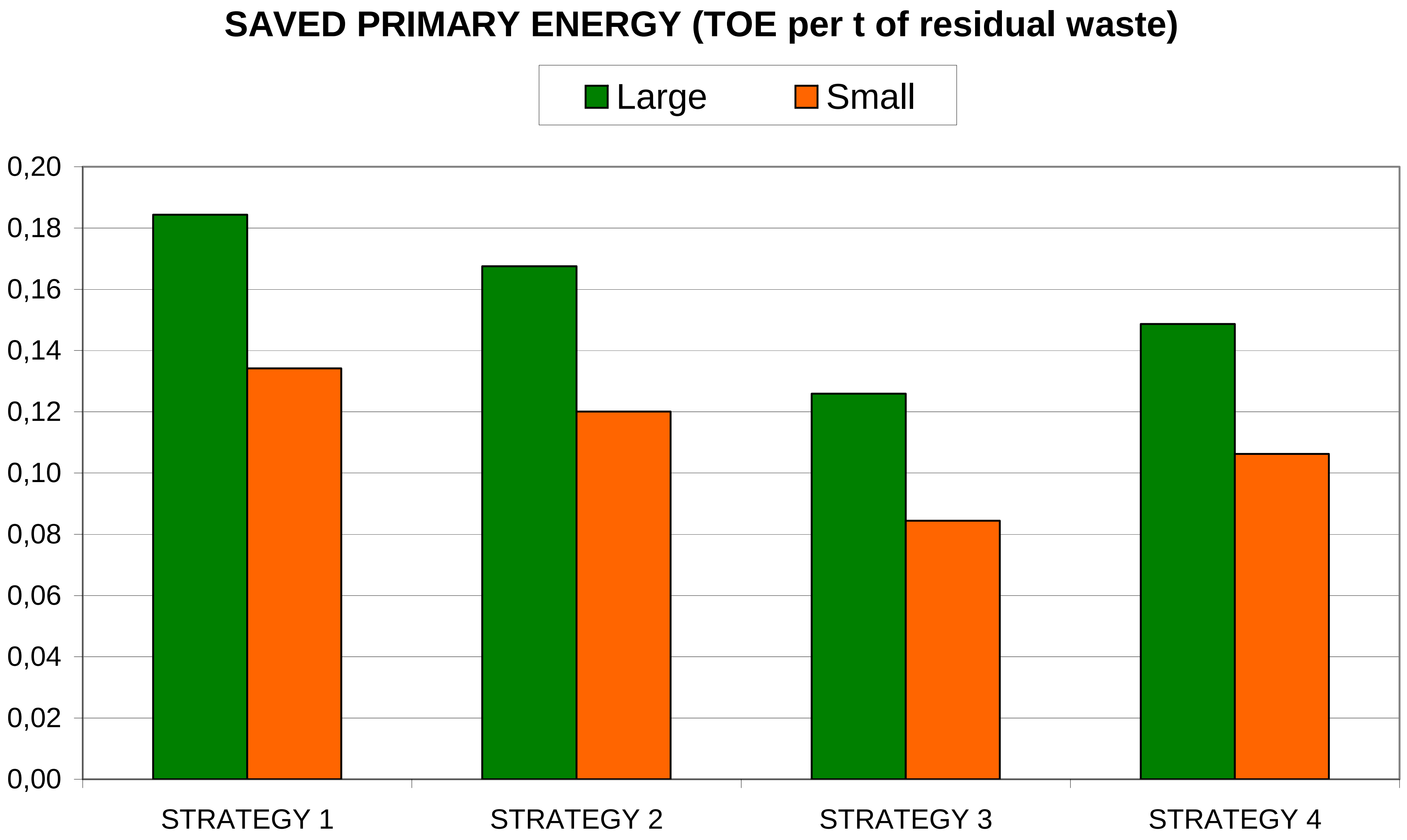
Overall energy balance

E=Electricity, F=Primary Energy, ER=Energy Recovery

ΔF=Variation of primary energy consumption

System size		Small				Large					
Strategy		1	2	3	4	1			2	3	4
WTE plant output		electricity				electr.	cog A	cog B	electricity		
E for pre treating	kWh_{el} per t of RW	0	17	118	60	0			17	118	60
E from WTE plant		588	544	526	527	807	699	587	751	707	712
net E		588	527	408	467	807	699	587	734	589	652
ΔF for el. generation	kgOE per t of RW	-134.9	-120.8	-93.6	-107.2	-185.1	-160.2	-134.7	-168.3	-135.2	-149.5
ΔF for heat generation							-55.3	-110.5			
F for pre-treatment		0	0	8.5	0	0	0	0	0	8.5	0
F for solids transport		0.8	0.9	0.6	0.6	0.8	0.8	0.8	0.9	0.6	0.6
net ΔF of ER		**-134.1**	**-119.9**	**-84.5**	**-106.6**	**-184.3**	**-214.7**	**-244.4**	**-167.4**	**-126.1**	**-148.9**
people served		200,000				1,200,000					
total energy use	TOE/yr	640,000				3,840,000					
net ΔF, absolute		**-8,716**	**-7,796**	**-5,493**	**-6,926**	**-71,896**	**-83,724**	**-95,322**	**-65,286**	**-49,179**	**-58,070**
net ΔF, relative	%	-1.36	-1.22	-0.86	-1.08	-1.87	-2.18	-2.48	-1.70	-1.28	-1.51

Overall energy balance



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Life Cycle Impact Indicators

All values referred to **1 t of Residual Waste**

Impact Indicators:

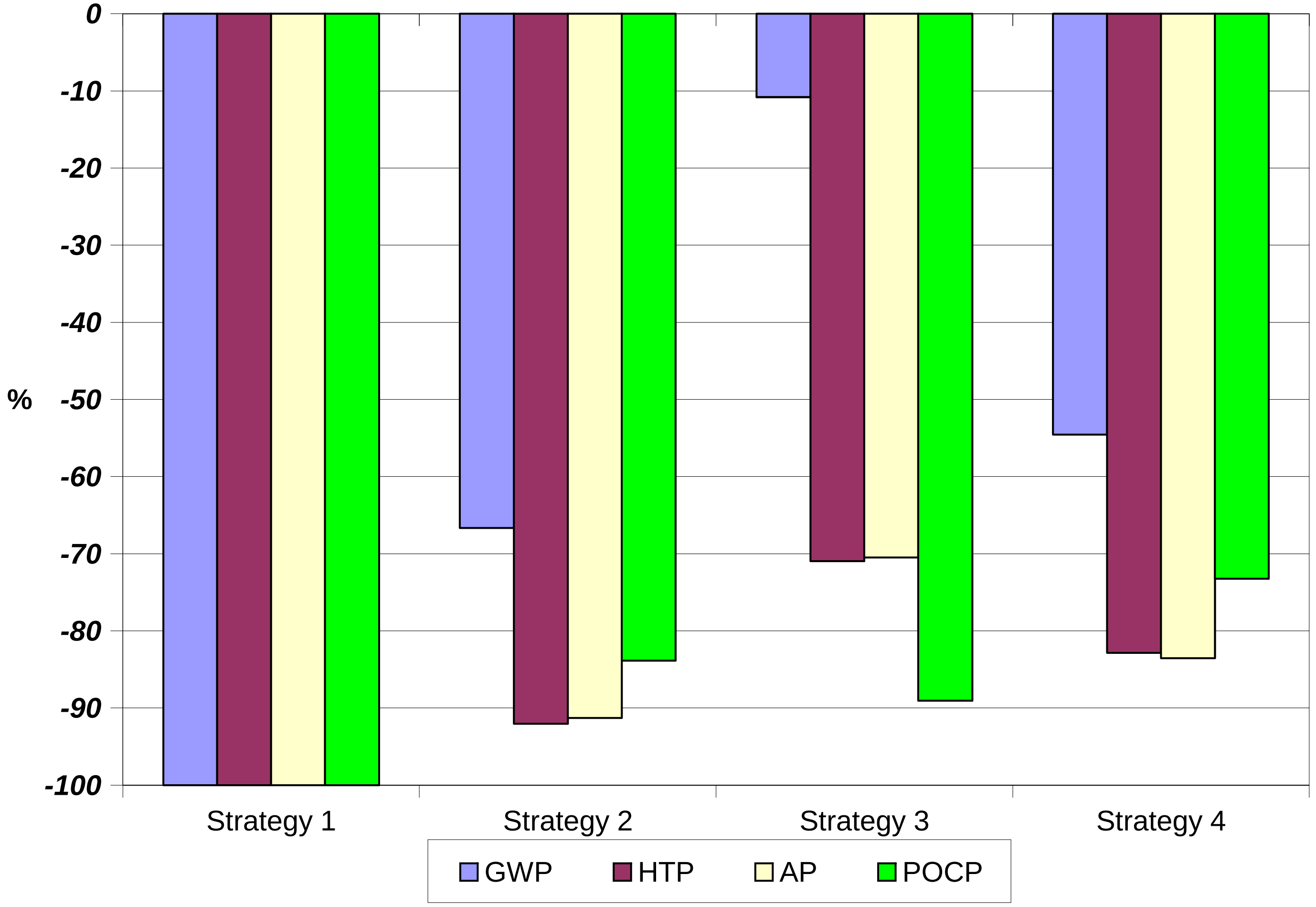
GWP = Global Warming Potential
HTP = Human Toxicity Potential
AP = Acidification Potential
POCP = Photochemical Ozone Creation Potential

WMS size		Small				Large					
Strategy		1	2	3	4	1			2	3	4
WTE plant output		electricity				electr.	cog A	cog B	electricity		
GWP	*kg CO_2 eq.*	101	111	122	102	-53,7	-134	-212	-35.8	-5.8	-29.3
HTP	*kg 1,4-DB eq.*	-69	-61.8	-43.9	-56.7	-113	-108	-102	-104	-80.2	-93.6
AP	*kg SO_2 eq.*	-2.14	-1.92	-1.38	-1.78	-3.22	-2.91	-2.59	-2.94	-2.27	-2.69
POCP	*kg C_2H_4 eq.*	-0.286	-0.237	-0.256	-0.206	-0.310	-0.309	-0.308	-0.26	-0.28	-0.23

Normalized Impact Indicators

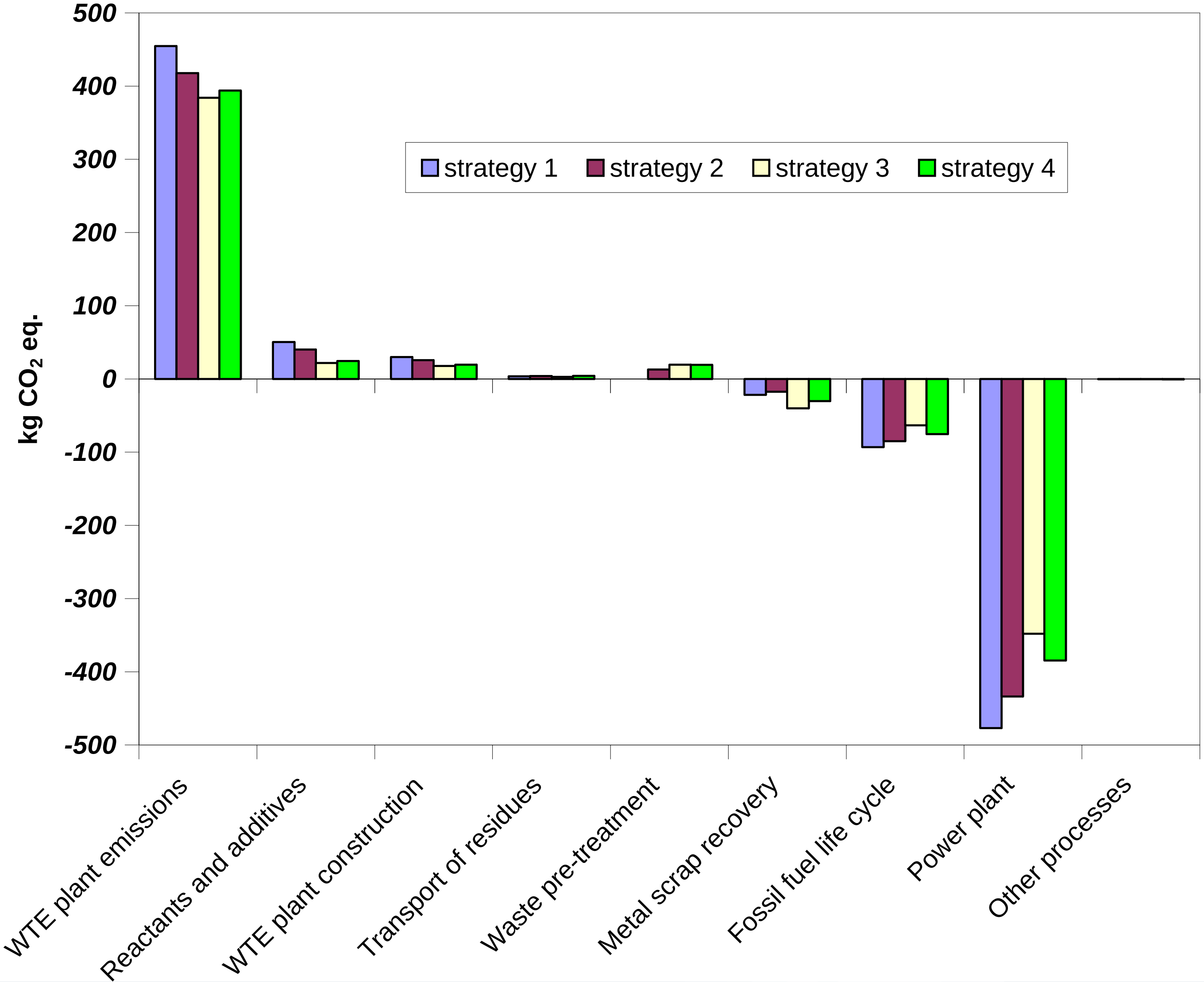
Results for **Large Systems**

Each impact indicator is non-dimensionalized with respect to the indicator of the best strategy, which is set to –100 %



Breakdown of GWP

Results for **Large Systems**



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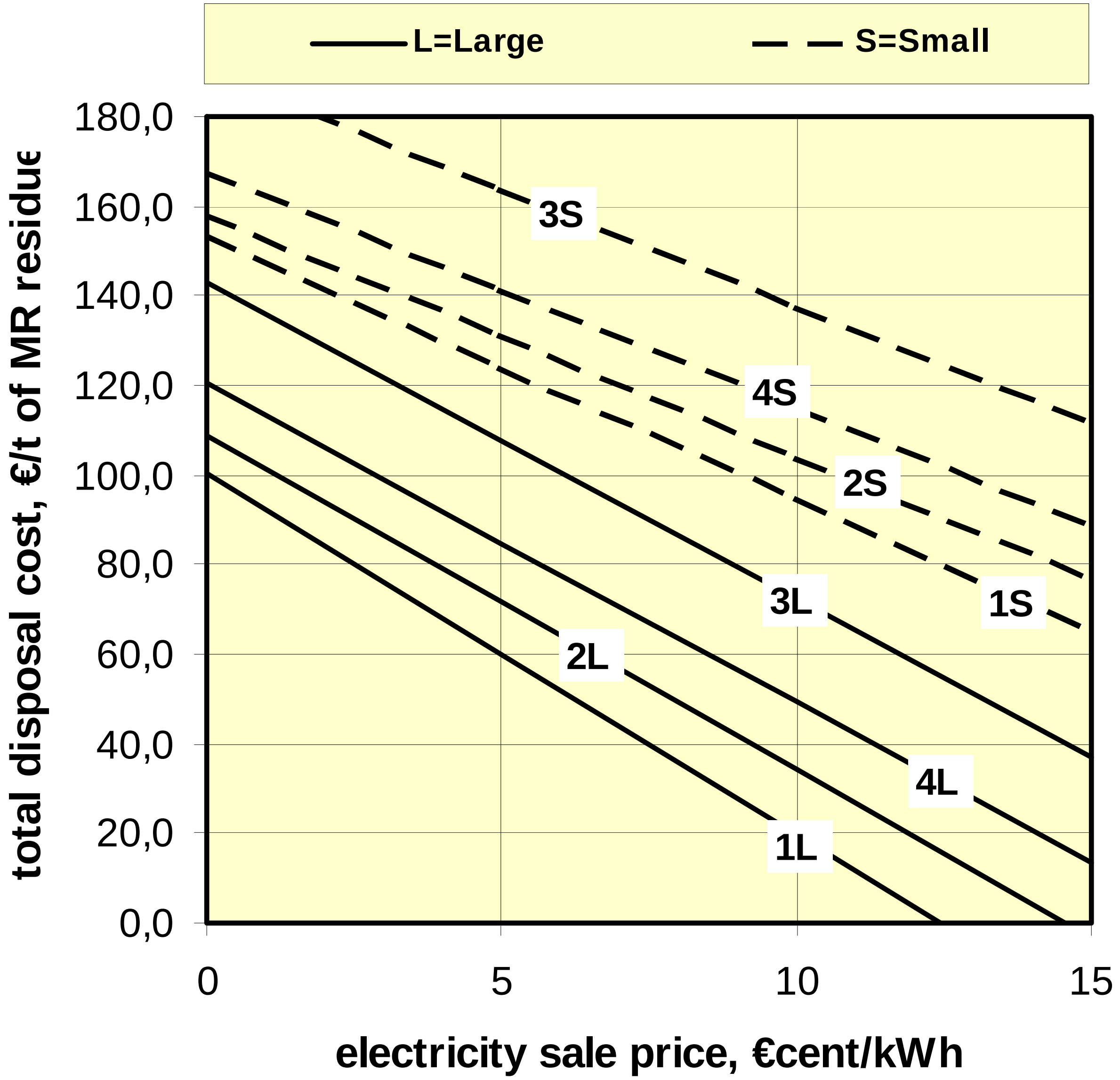
Costs: RDF production

System size				small				large			
Gross MSW production			t/yr	100,000				600,000			
Residual Waste (RW)			t/yr	65,000				390,000			
Strategy				1	2	3	4	1	2	3	4
“light” treatment	mechanical treatment	input flow	t/yr		65,000				390,000		
		capital + personnel+ O&M	€/t		20				20		
			M€/yr		1.3				7.8		
	SOF	production	t/yr		7,800				46,800		
		disposal	€/t		20				20		
		cost	M€/yr		0.156				0.936		
	total		M€/yr		1.456				8.736		
		€ per t treated			**22.4**				**22.4**		
RDF production	all treatments	input flow	t/yr			65,000	65,000			390,000	390,000
		capital + personnel+ O&M	€/t			65	40			65	40
			M€/yr			4.225	2.6			25.35	15.6
	SOF	production	t/yr				9,750				58,500
		disposal	€/t				20				20
		cost	M€/yr				0.195				1.17
	inert materials	production	t/yr			8,190	5,330			49,140	31,980
		disposal	€/t			40				40	
		cost	M€/yr			0.328	0.213			1.966	1.279
	total		M€/yr			4.553	3,008			27.316	18.049
		€ per t treated				**70.0**	**46.3**			**70.0**	**46.3**

Overall costs

WMS size				small				large			
Gross MSW production			t/yr	100,000				600,000			
Residual Waste (RW)			t/yr	65,000				390,000			
Strategy				1	2	3	4	1	2	3	4
WTE plant	input flow		t/yr	65,000	51,977	34,635	38,977	390,000	311,864	207,807	233,864
	combustion power		MW_{LHV}	25.4	23.4	22.2	22.4	152.1	140.5	132.9	134.5
	capital + O&M + contingencies		€/kW_{LHV}-yr	250				160			
			M€/yr	6.337	5.853	5.537	5.602	24.295	22.438	21.225	21.477
	Reactants		€/t combusted	3.6		3.0		3.6		3.0	
			M€/yr	0.234	0.187	0.104	0.117	1.404	1.123	0.623	0.702
	Personnel		units	43	41	40	40	85	82	80	80
			€/unit-yr	40,000							
			M€/yr	1.72	1.64	1.6	1.6	3.4	3.28	3.2	3.2
	bottom + fly ashes	production	t/yr	16,835	11,570	5,720	5,850	101,010	69,420	34,320	35,100
		disposal	€/t	100.0							
		cost	M€/yr	1.683	1.157	0.572	0.585	10.101	6.942	3.432	3.510
	electricity production		kWh/t combusted	588	680	987	879	807	938	1,327	1,186
		net to grid	MWh/yr	38,220	35,345	34,184	34,261	314,730	292,528	275,760	277,362
		net	€cent/kWh	5.0							
		revenues	M€/yr	1.911	1.767	1.709	1.713	15.737	14.626	13.788	13.868
	total$^{(2)}$		M€/yr	8.064	7.070	6.103	6.191	23.464	19.157	14.693	15.020
			€ per t combusted	**124**	**136**	**176**	**159**	**60**	**61**	**71**	**64**
total cost			M€/yr	8.064	8.526	10.656	9.199	23.464	27.893	42.008	33.069
			€ per t of RW	**124**	**131**	**164**	**142**	**60**	**72**	**108**	**85**
			Increase vs. strategy 1, %	-	5.7	32.1	14.1	-	18.9	79.0	40.9

Total disposal cost



Conclusions

1. Producing RDF to subsequently use it in dedicated plants appears to offer no advantage over the "direct" use of Residual Waste in grate combustor WTE plants
2. Compared to "direct" energy recovery, strategies with {RDF+dedicated plants} reduce energy savings by 10-40%, reduce environmental indicators by up to 90% and increase costs by up to 80%.
3. The more sophisticated and complex is the process adopted to produce RDF, the higher the losses
4. Economies of scale give a very strong advantage to large Waste Management Systems
5. For dedicated plants, best option is large cogenerative WTE plant with direct feed of Residual Waste

Work in progress

1. Comparison between "direct" energy recovery (strategy 1) and {RDF+co-combustion} in non-dedicated plants (strategies 5 and 6) gives a more complex situation: no strategy "wins" across the whole spectrum of indicators.
2. {RDF+co-combustion} tends to make more sense for small systems, particularly in terms of lower GWP
3. "Direct" energy recovery from Residual Waste by cogenerative grate combustors tend to prevail for large systems
4. Risk of adverse, long-term effects of co-combustion must be assessed through operating experience

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– environmentally benign,
– energy efficient,
– cost effective
strategies to recover energy from waste

All of you for your attention !