Extended Abstract

Technical and economic evaluation of the application of Waste to Energy systems in the treatment of MSW on Small and Medium-sized regions

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Abstract

Per day are produced in Portugal 12.600 tons of Municipal Solid Waste (MSW). The thermal treatment (incineration) represents about 22% of the final destination of the waste produced, which reduces by about 2,000 tons the amount of waste disposed daily to landfill. It was estimated for five municipal waste incineration facilities in Portugal the *levelized costs*. The thermal treatment costs were analyzed in a wide-ranging values of capacities (approximately between 120 and 2.000 t/day). It was found that the treatment cost reflect the economy of scale (with an exponent factor of n equals to 0.6), ranging between 27.7 and 21.8 €/t for VALORSUL and LIPOR facilities; and between 72.5 and 39.1 €/t for the units that constitutes 3 municipal systems existing in the regions of Madeira and Azores (ARM, AMISM and TERAMB). Rcently have increased the level of installation of Energos® technology units (gasification system), especially in the UK and Norway. It was concluded that, for this system, the actual cost of treatment is identical to that of conventional incineration existing in Terceira Island (67.6 €/t) for the same inflow capacity (40 kt/year) and LHV (8 MJ/kg). In fact, the total cost (non-revenues accounted) is higher, but if one takes into account the energy production, both systems costs are similar, which shows that in regions where the small scales systems are required, gasification, in particular Energos® technology, is presented as a viable technical and economically alternative.

Keywords: *Waste-to-Energy, incineration, MSW, treatment costs, Advanced Thermal treatments (ATT)*

1. Introduction

In general, the thermal treatment systems currently available still represent successive technological advances, particularly in terms of ways of obtaining energy and emission control and waste products. Thus, it has been falling into disuse the term 'incineration', having come this to be replaced by "Waste to Energy" (WTE) or 'Energy from Waste' (EfW).

In order to establish the estimation bases the treatment cost of incineration in Portugal, it was estimated (for five municipal waste incineration plants) the *levelized costs*, i.e. the values of effectiveness costs obtained were expressed in euros (€) per ton (t) of waste. The energy recovery units planned for the Terceira Island and São Miguel Island represent much smaller capacitys than the previously existing systems, which allowed studying the thermal treatment costs in a wide-ranging values of capacities (approximately between 120 and 2.000 t/day).

2. Waste Management

In Portugal are produced annually 14,3 Mt of waste, of which 4.6 Mt correspond to Municipal Solid Waste (MSW) (PERSU, 2020; APA, 2014).

Under Decree-Law No. 73/2011 sets up Municipal Solid Waste as “waste from households and other waste which by its nature or composition, is similar to waste from households”.

Table 2.1 shows the average composition of the waste produced in OECD countries. In addition, the average physical characterization of MSW produced specifically in Portugal can also be viewed in **Table 2.1**, as well as the lower heating value (LHV) of existing materials in an undifferentiated mass of municipal solid waste.

Under Decree-Law No. 78/2004 sets up PCI as "the amount of heat released by the complete combustion of a unit volume or mass of a fuel, when burned completely at a certain temperature, remaining combustion products in the gas phase (without condensation of water vapor). "

It is common use to this parameter in the mass balance of thermal treatments, as this indicator is the potential energy that can be harnessed.

Table 2.1: Average physical characterization and PCI of MSW produced: (a) Vainikka et al. (2012), (b) and OECD (c) Portugal.

Component	Vainikka (2012) (%)	Countries OCDE[1] (%)	Portugal[2] (%)	LHV (MJ/kg)
Organics and food	30 - 40	27	37	1,9[3]
Paper/Card	15 - 25	32	13	10,6[4]
Plastic	7 - 15	11	11	31,5[4]
Glass	4 - 7	7	5	0[4]
Metals	3 - 4	6	2	0[4]
Others	18 -30	17[4]	32	-
MSW	100	100	100	10,4[5]

[1]Hoornweg e Bhada-Tata (2012); [2]APA (2014) [3]Rand et al. (1999); [4]Leckner (2014); [5]European IPPC Bureau (2006);

Note that the treatments through landfills (disposal operation) are the main source of GHGs emissions. In a study for Portugal (called "Impact of options and Waste Management Opportunities in the Mitigation of Greenhouse Gas Effect in Portugal") it is estimated that the production of energy through incineration is responsible for an indirect reduction 0,18 tCO2eq per tonne of waste according to PERSU II.

A waste management system that considers 4 main vectors - the collection, transport, recovery and disposal of waste - which includes the supervision of such operations and maintenance of disposal sites in post-closure.

The Decree No. 73/2011 defines the concepts of “recovery” and “disposal” respectively:
• "(...) as any operation whose main result is the transformation of the waste serving a useful purpose by replacing other materials which would otherwise have been used for a specific purpose or waste being prepared for this purpose in the plant or the economy ';
• "(...) as any operation that is not recovery yet to occur as a secondary consequence the reclamation of substances or energy."

It can be seen in **Fig. 2.5** the direct final destination that the waste are subjected Portugal. It appears that the landfill, although it is the less desirable destination, continues to represent 43% of the final destination of the urban waste. In turn, incineration (energy recovery) had in 2013 a significant expression of 22% - which is due to the scale of the implemented incineration systems in Lisbon (VALORSUL) and Porto (LIPOR), which allows you to handle large amounts of waste from major urban centers.

Treatment for organic recovery is only 2% of the national territory and recycling, despite their importance in MSW management for now is only 9%. It should be noted, however, that the forwarding of waste to a landfill, if the waste and/or reject other types of treatments are considered, is much higher, representing about 60% of total residues in Portugal (APA, 2014).

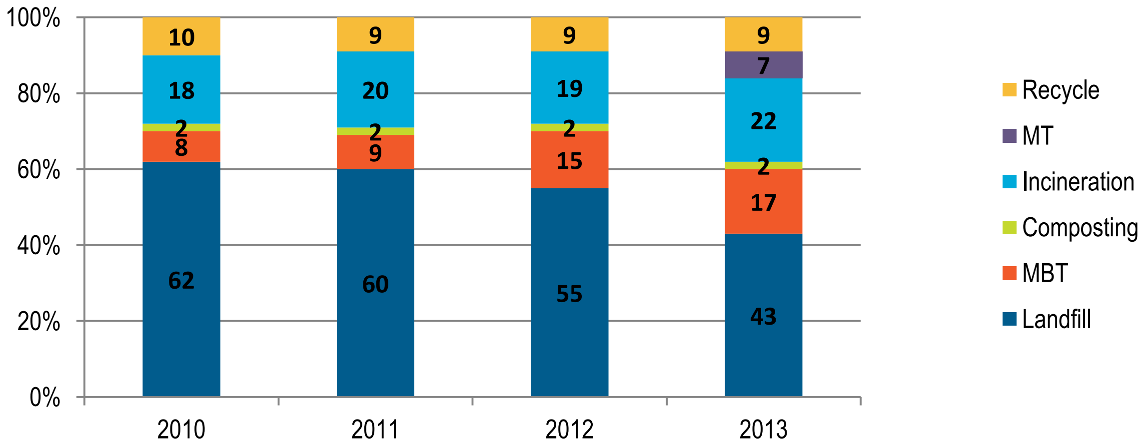

Fig. 2.1: Final direct destination of waste in Portugal. Adapted from APA (2014)

3. Thermal treatment

The thermal treatment of waste consists essentially in processing waste by means of thermal processes with significant volume reduction (from 80 to 90%) and weight (70 to 80%) (Arena, 2012). Upon receipt of the waste, the treatment process starts in a combustion chamber with a source of thermal ignition promoting waste oxidation process (exothermic reaction) releasing the heat energy of the waste, which by means of certain acquisition devices energy can be utilized in the form of electricity, heat, or stored in the form of energy products.

There are mainly three types of systems that compose the thermal waste treatment, which are characterized by the terms associated thermochemical process (Arena, 2012):

- Incineration
    - By Combustion;
- Advanced Thermal Treatment (ATT)
    - Gasification;
    - Pyrolysis.

The predominant system is incineration, which are created conditions for waste is fully oxidized (combustion). On the other hand, in systems gasification and pyrolysis residues are oxidized in sub-stoichiometric conditions (air ratio <1) resulting gaseous products with considerable energy value (syngas) (Leckner, 2014). Thus, the synthetic gas burning under certain conditions allows not only produce electricity and/or heat energy efficient but also a wide range of energy products (Arena, 2012).

The main differences can be seen in **Table 3.2.**

Table 3.2: Typical conditions of reactions and products generated during pyrolysis processes, gasification and combustion. Adapted from European IPPC Bureau (2006).

Process	Pyrolysis	Gasification	Combustion
Temperature (°C)	250 - 700	500 - 1600	800 - 1450
Pressor (bar)	1	1 - 45	1
Atmosphere	Inert, nitrogen	Oxidation process	Air
Oxygenic Ratio	0	<1	>1
Resulting Products			
gaseous	H2, CO, hidrocarbons, H_2O, N_2	H_2, CO, CO_2, CH_4, H_2O, N_2	CO_2, H_2O, O_2, N_2O
solid	Ash, coke	slags, ash	slags, ash
liquid	Pirolitic oil e H_2O		

According to Stein (2004) the volume of gas resulting from the ATT is much smaller which allows have smaller cleaning gases technologies and even cheaper.

Moreover, the restriction in oxygen levels is not conducive to the formation of dioxins and furans (Grieco and Baldi, 2012), so that the ATT solutions are usually less polluting.

In terms of energy production, energy acquisition devices associated with the synthetic gas (turbine or gas engine) has energy efficiencies higher than the steam turbine (Rankine cycle) typically associated with conventional incineration systems (Grieco and Baldi, 2012; Lettieri et al., 2010).

In order to classify the scale such systems, it is assumed the definition proposed by (Reimann, 2009) establishing the scale of plants depending on the project capacity or feed rate, although other scaling settings WTE units admit other limits. Brackets were placed values expressed expected tons per day, based on an actual annual operating period of the year 90%, or 7884 hours. So it is assumed:

- Small scale: less than 100,000 t / year (approx less than 300 t / day.)
- Medium scale: between 100.00 and 250,000 t / year (about 300 to 760 t / day.)
- Large scale: over 250,000 t / year (about more than 760 t / day.)
-

4. WTE Technologies

The main combustion by incineration technologies are based on the following reactors / conversion systems – moving grate, fluidized bed and rotary kiln. This phase corresponds to the main phase of thermal conversion, where waste is actually processed. (A subsequent phase corresponds to the energy recovery phase, which may or may not be uncoupled from the previous phase).

To produce electricity there are two options. In its most simplistic form: to use the steam generated by the oxidation of gas to drive a turbine coupled to a generator so similar to what is done in incineration plants. However, steam production, in these conditions, has a similar efficiency for both incineration by combustion and for TTA.

However, the production of electricity can follow another route: the filtrate is subjected to a gas combustion chamber which is responsible for directly actuate a turbine or gas engine, with better results on efficiency of the units.

4. Cost of systems

In the cost analysis carried out in relation to energy recovery units the following assumptions were admitted:

- The analysis was carried out at 2016 constant prices, measured in euros (€).
- The values obtained in dollars ($) were converted at a rate of 0.895 ($ for €)

- The time cost updates (inflation) were obtained based on the rates of change of the Consumer Price Index, according to the *Instituto Nacional de Estatística* (INE)
- Operating costs and calculated income were levelized taking into account the operational capability of the systems, which is assumed equal to the average quantity of waste incinerated per year in the last seven complete operation years (2009-2015).
- Where the (s) unit (s) of recovery implemented less than a full year of operation or whose implementation is expected in a short time, was admitted to the operational capacity of equivalent systems to 90% of design capacity (i.e. 90% availability).
- The amortization cost (financing) was levelized taking into account the average operational capacity expected over the lifetime of the unit, which was assumed equivalent to 90% of design capacity.
- Applied to the reference tariff (electricity) of 94.6 €/MWh.

The following components of costs and income were estimated in euros per tonne of waste inflowto (€/t), excluding the cost of investment identified in Euros (€):

Investment costs (C_i)

Investment costs represent the amount of capital invested in the initial phase of the project in the implementation phase of the project and is expressed in € 10^6.

Total annual cost of treatment (C_t)

$$C_t = C_i \frac{i\,(1+i)^n}{(1+i)^n - 1} + C_o = C_a + C_o \tag{4}$$

Where:

C_i – *Investment cost*

C_o – *Operating cost*

C_a – *Amortization*

i – *Amortization rate*

n – *Amortization period*

Operating costs (C_o):

$$C_{o,year\ i} = \frac{C_{o,fixed} \times Nominal\ capacity + C_{o,variable} \times E_{electricity,gross}}{Cap._{operacional,year\ i}} \tag{5}$$

Where:

$C_{o,\text{ year i}}$ – $operating\ costs$ (€/t)

$C_{o,\text{ fixed}}$ – $fixed\ operating\ cost$ (€/kW.ano)

$Nominal\ capacity$ – $Capacity\ of\ electricity\ production$ (kW)

$C_{o,variables}$ – *variable operating costs* (€/MWh)

$E_{electricity,gross}$ – *Produced electricity* (MWh)

$Cap._{operacional,year\ i}$ – *quantity of waste incinerate* (t)

The fixed operating costs and variable operating costs are expressed in **Table 5.1**.

Table 5.1: fixed and variable operating costs (at 2016 prices). Adapted by EIA (2013)

Parameters	Facilitie	Units
Fixed operating costs[1]	351,62	€/kW.year
Variable operating costs[1]	7,83	€/MWh

[1] Prices updated in 2016; conversion factor of 0.895 dollar to euros

Annual amortization (C_a)

$$C_a = \frac{C_i}{Cap._{operacional,year\ i}} \frac{i\,(1+i)^n}{(1+i)^n - 1} = \frac{C_i}{Cap._{operacional,year\ i}} \times f_a \qquad (6)$$

Wheres:

C_a - *Amortization costs (€/t)*

C_i - *Investment costs (10^6 €)*

$Cap._{operacional,year\ i}$ – *quantity of waste incinerate* (t)

i – *Amortization rate*

n – *Amortization period (years)*

f_a – *Amortization factor*

Income or Revenue (R)

$$R_{year,i} = \frac{P_{elect.} \times E_{electricity,net}}{Cap_{,op,ano\ i}} \qquad (7)$$

Where:

$R_{year\ i}$- *Revenue year, i* (€/t)

$P_{elect.}$ – *Price of electricity(€/kWh)*

$E_{electricity,\ net}$ – *quantity of sold electricity (Wh)*

$Cap_{,op,ano\ i}$ – *quantity of waste incinerate (t)*

Effective cost or net cost (C_e)

Thus, it is assumed that net cos tis given by expression (8).

$$C_e = F(C_O, C_a, R) = \sum C_i - \sum R_i = C_O + C_a - R \qquad (8)$$

7. Comparative analysis

In terms of investment cost, yielded cost functions for the sample plants studied, are systematized in **Table 7.1.**

Table 7.1: Investment costs functions approximate WTE units in Portugal and Europe (to 2016 prices)

Parameters	Facilities in Portugal	Facilities in Europe	Units
Sample	5 facilities	32 facilities	-
Design capacity (x)	40 - 662	20 - 600	kt/year
Investment cost (y)	$1{,}83 \times^{0.8}$	$1{,}50 \times^{0.8}$	M€
Determination coefficient (R^2)	0,955	0,890	-

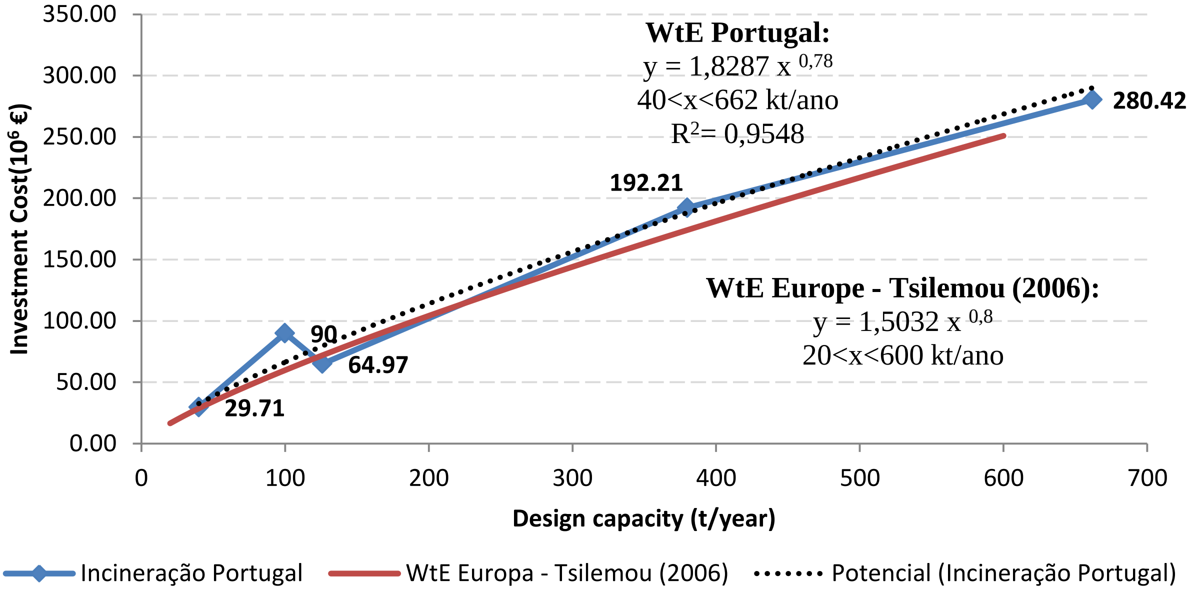

Fig. 7.1: Investment costs of the WTE plants in Portugal and Europe.

The results obtained are Systematized in **Table 7.2 and Fig. 7.2**

Table 7.2: Net cost of thermal treatment in WTE facilities in Portugal (the 2016 prices)

Parameters	Facilities in Portugal	Units
Sample	5 facilities	-
Design capacity (x)	40 - 662	kt/year
Net cost (y)	$391{,}6 \times^{-0{,}441}$	€/t
Determination coefficient (R^2)	0,85	-

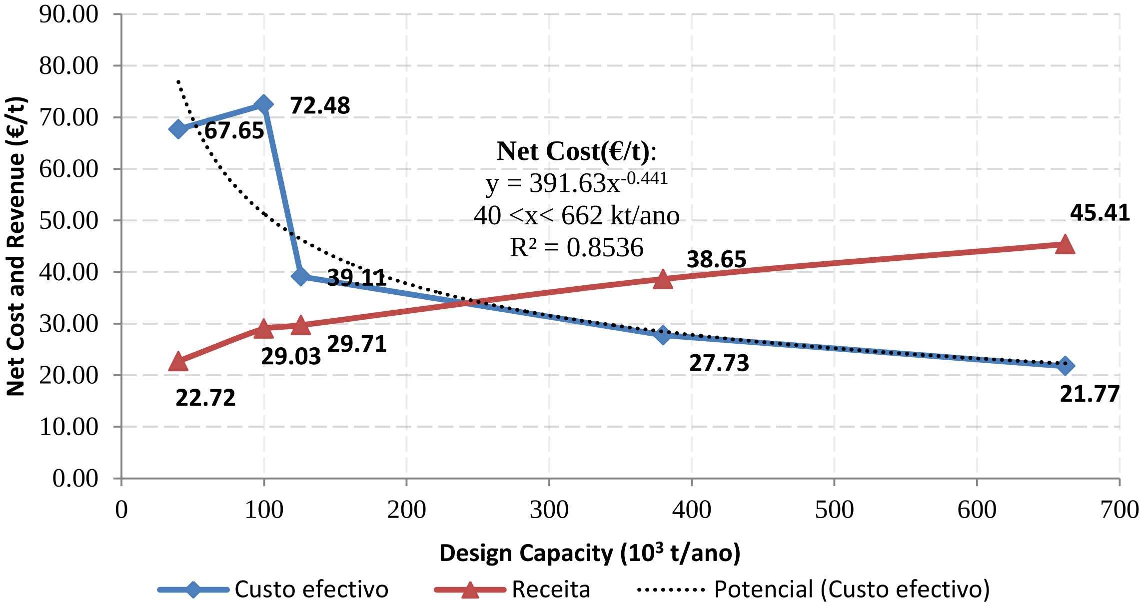

Fig. 7.2: Net cost effective and revenue of thermal treatment on WTE plants in Portugal

Therefore, regardless of the availability of systems, you can determine the scale factor (n) associated with the actual cost of the systems in absolute terms (in €):

$$n = 1 - 0.441 = 0.559 \cong 0.6$$

The calculation.is systematized in **Table 7.3.**

Table 7.3: Comparison of the actual cost of thermal treatment on WtE unit of Terceira Island and Energos® with capacity of 40 kt/year (2016 prices)

Parameters	Island Terceira (Incineration)	Energos® (Gasification)	Units
Project capacity (x)	40	40	kt/year
Net cost (y)	67,65	66,61	€/t
Relation	67.65/66.61 = 1,016		-

8. Conclusions and Future Work

Due to technological development of incineration technologies (Waste-to-Energy), it is possible to obtain an electrical output, in Portugal, between 400 and 500 kWh per ton of waste processed, depending on scale variability. Following the policies defined at European level, it has been found that one of the priorities in waste management sector keep being the reduction of biodegradable residues disposed to landfill, in order to eliminate a major source of greenhouse gases emissions (GGEs). In this context, waste incineration permits indirectly a reduction of 0.18 tCO2eq. for each tonne of waste processed in energy recovery units. It was found that the treatment cost reflect the economy of scale (with an exponent factor of n equals to 0.6), ranging between 27.7 and 21.8 €/t for VALORSUL and

LIPOR facilities, that represent the level of service in two biggest urban areas; and between 72.5 and 39.1 €/t for the units that constitutes 3 municipal systems existing in the regions of Madeira and Azores (ARM, AMISM and TERAMB). In similarity of energy recovery technologies existing in Portugal, throughout Europe predominate (about 90%) conventional incineration systems (i.e. combustion in grate furnace with a boiler steam turbine), but have increased the level of installation of Energos® technology units (gasification system), especially in the UK and Norway. This technology is part of the so-called advanced thermal treatments (ATT), which are characterized by their compact conception, generally much smaller than conventional technologies. It was concluded that, for this system, the actual cost of treatment is identical to that of conventional incineration existing in Terceira Island (€ 67.6 / t) for the same inflow capacity (40 kt/year) and LHV (8 MJ / kg). In fact, the total cost (non-revenues accounted) is higher, but if one takes into account the energy production, both systems costs are similar, which shows that in regions where the small scales systems are required, gasification, in particular Energos® technology, is presented as a viable technical and economically alternative.

References

Agência Portuguesa do Ambiente (APA), Silva F., Mateus I., Marçal A., Ricardo S., Pires S., Relatório Anual de resíduos urbanos 2013, I.P (2014).

Plano Estratégico para os Resíduos Sólidos Urbanos (PERSU 2020), Lisboa : Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional, 2014

Vainikka, P., Tsupari E., Sipila K., Hupa, M., Comparing the greenhouse gas emissions from three alternative waste combustion concepts, Waste Management 32 (2012), no. 3, 426–437.

Hoornweg, D., Bhada-Tata, P., 2012. *What a waste: a global review of solid waste management*. Urban development series. Knowledge papers no. 15. Washington, DC: World Bank.

Agência Portuguesa do Ambiente (APA), Silva F., Mateus I., Marçal A., Ricardo S., Pires S., *Relatório Anual de resíduos urbanos 2013*, I.P (2014).

Rand, T., Haukohl J., Marxen, U., *Municipal solid waste incineration*, Municipal waste combustion (1999).

Leckner, B., *Process aspects in combustion and gasification Waste-to-Energy (WtE) units*, Waste Management (2014).

European IPPC Bureau, *Reference document on the Best Available Techniques for Waste Incineration*, Integrated Pollution Prevention Control (2006).

Plano Estratégico para os Resíduos Sólidos Urbanos (PERSU II), Lisboa : Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional, 2007.

Arena, U., *Process and technological aspects of municipal solid waste gasification. A review*, Waste Management 32 (2012), no. 4, 625–639.

Stein, W., *Review of Small Scale Waste To Energy Conversion Systems*, Renewable Energy (2004).

Grieco E.M., and Baldi, G. Pyrolysis of polyethylene mixed with paper and wood: Interaction effects on tar, char and gas yields, Waste Management 32 (2012), no. 5, 833–839.

Reimann, D.O., *CEWEP Energy Report II (Status 2004–2007), Results of Specific Data for Energy, R1 Plant Efficiency factor and Net Calorific Value (NCV) of 231 European WtE Plants* (2009)