Waste-to-Energy and recycling: How do plant ownership and waste mobility affect equilibrium outcomes?

Laura Levaggi[*], Rosella Levaggi[†], Carmen Marchiori[‡], Carmine Trecroci [§]

25th January 2019

Abstract

This paper investigates incentives, trade-offs and equilibria in a simplified two-Region model of the final treatment of municipal solid waste. The two regions are identical but for the waste disposal facilities operating in each region, which are: a Waste to Energy (WtE) plant in Region 1, and a landfill in Region 2. In this setting, and in the absence of spillovers, we investigate how waste mobility and the institutional setting (public/private ownership of the WtE plant) affect waste management choices and welfare in the two Regions. When waste mobility across Regions is not allowed, the institutional setting is uninfluential, but it does not necessarily minimise its environmental damage. Allowing for mobility when the incinerator is publicly owned, leads to an equilibrium outcome which is both globally efficient and Pareto improving for the two Regions. Compared to the no-mobility case, the optimal level of recycling is higher in Region 1 and lower in Region 2; moreover, the total amount of waste incinerated is larger. Finally, the mobility scenario with private ownership may not be welfare improving for all parties involved.

Keywords: WtE technology, waste mobility, welfare

J.E.L. codes: H70, D62, Q20.

[*]Faculty of Science and Technology, Free University of Bolzano-Bozen, Piazza Università 1, 39100 Bolzano-Bozen, Italy, laura.levaggi@unibz.it

[†]Department of Economics and Management, University of Brescia, Italy; rosella.levaggi@unibs.it

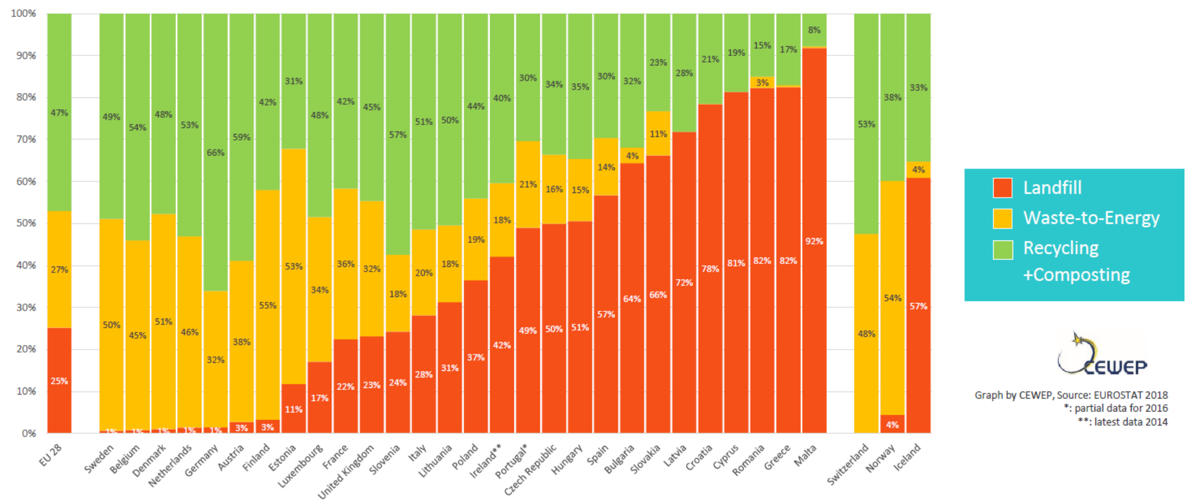
[‡]Department of Economics and Management, University of Brescia, Italy; carmen.marchiori@unibs.it

[§]Department of Economics and Management, University of Brescia, Italy; carmine.trecroci@unibs.it

1 Introduction

The role of Waste-to-Energy (WtE) facilities for the disposal of waste is very controversial across countries because of its complex economic and environmental implications. Compared to conventional power generation sources, WtE is a costlier option; however, demand for incineration services is growing for several reasons. On one hand, new-generation WtE plants in a combined heat and power mode (CHP) attain enhanced efficiency levels and larger economies of scale compared to older facilities, more so thanks to the continued expansion of district heating systems. On the other hand, following concerns about greenhouse gas emissions and pressure on local ecosystems, authorities are rapidly phasing out landfill dumping. In this paper, we propose a parsimonious theoretical model to study the effects that institutional settings and market discipline have on waste disposal and recycling in the presence of efficient WtE technology. In Europe and around the world, waste generation rates are rising ([Eurostat, 2018, Bank, 2018]. The incineration of municipal waste in the EU-28 has risen by 112% between 1995 and 2016, whereas per capita generated waste has grown by only 2.1%. At EU level, public authorities ([EEA, 2013, EPA, 2014, DEFRA, 2014, EEA, 2016, EUCOMM, 2017b, EUCOMM, 2017a] advocate a well-known ranking of waste management practices. Reducing the need for new materials should be the top priority, followed by reuse, recycling, waste-to-energy incineration and placement in a landfill. Figure 1 shows the share of recycling and composting, waste-to-energy and landfilling of treated municipal waste in EU28 Member States (plus Iceland, Norway and Switzerland).

The data show very diverse systems of treatment across the EU: while recycling, composting and waste-to-energy are on a robust rising trend and landfilling is shrinking, the latter is still the preferred or the second most important option in many countries. This non-homogeneous picture is clearly the result of past legislative innovations and institutional differences that we aim to analyse. The 2008 Waste Framework Directive introduced some important changes in the European waste market, with complex effects on waste management. While the Directive strengthened the principles of waste prevention, proximity and self-sufficiency, it also fostered the shipment of waste between countries, provided it is treated in waste incineration facilities with energy recovery (see [Persson and Münster, 2016] for further discussion and perspectives). However, as the public's support towards WtE plants remains mixed, the facilities' optimal incineration capacity often exceeds the local supply of waste to be disposed of. In some countries and regions the deployment of WtE plants is



Source: [CEWEP, 2018] based on Eurostat data

Figure 1: EU28 (plus Iceland, Norway and Switzerland), share of recycling and composting, waste-to-energy and landfilling of treated municipal waste, 2016. Source: Confederation of European Waste-to-Energy Plants.

very sparse. For instance, Figure 2 tracks the location of WtE plants in Italy and Spain, whereas [Persson and Münster, 2016] show that incineration capacity normalised to population is quite unevenly spread across NUTS2 regions in Europe.

Coupled with the rising trend of recycling rates, the geographical concentration of efficient incineration capacity imply substantial flows of waste from farther away towards WtE plants, with rising environmental and operational costs. The construction of large and efficient WtE technologies imply complex political-economy interactions. For instance, those facilities may affect the public's attitude towards waste [[Fredriksson, 2000]] and the incentives to recycle. At a policy level, the compatibility between recycling and waste-to-energy is debated within two opposite views ([Viscusi et al., 2011, Cecere et al., 2014, D'Amato et al., 2016]). On the one side, supporters of incineration argue that recycling and waste-to-energy are complementary and that the presence of WtE plants correlates with high recycling rates in communities. On the other hand, opponents argue that the presence and size of such facilities introduces significant distortions that discourage a community's recycling efforts. In Sweden, for instance, the common view is that they are a safe and efficient way to produce energy. In 2016, nearly 2.3 million tonnes of household waste was burned into energy but

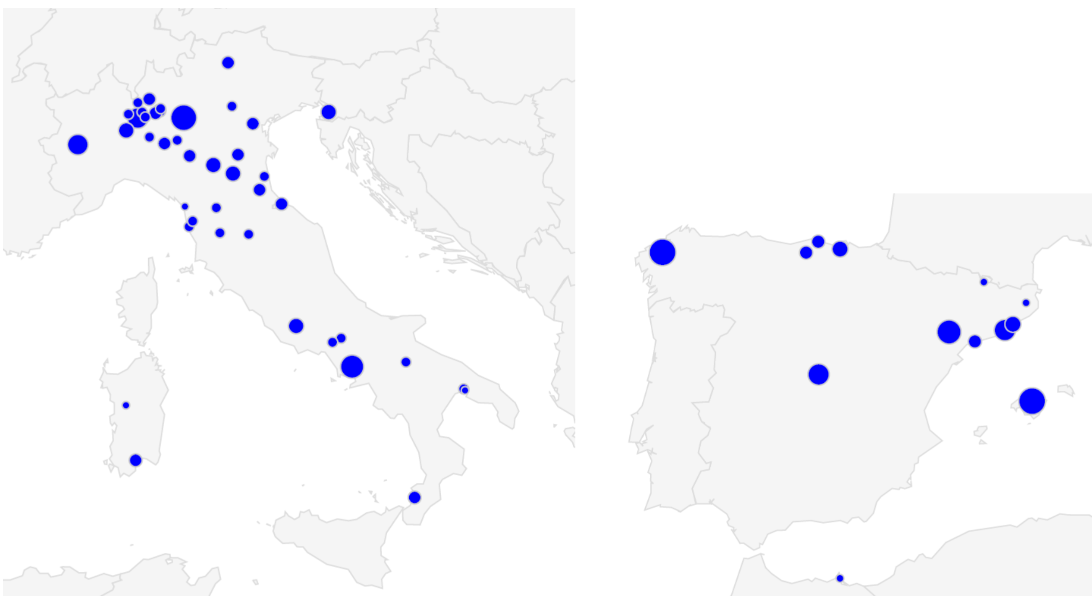


Figure 2: WtE plants in Italy and Spain, 2016. The points' size reflect each facility's treating capacity.

local WtE plants had to import about the same amount from, among others, Norway, the UK and Ireland [1]. A similar picture applies to Denmark, Norway and the Netherlands. In the UK, a large exporter of valuable to-be-incinerated waste towards continental Europe, waste shipment is coming under scrutiny for opposite reasons: the question is about the desirability of exporting a potential source of energy [2]. Besides the recurrent concerns about the environmental damages of waste shipments and WtE technology, the impact on recycling rates is ambiguous. At the national level, countries with strong incineration capacity tend to have higher-than-average recycling and composting rates. However, cities and regions that host large WtE facilities often display lower recycling rates. There are interesting welfare implications of decentralization and waste mobility ([Levaggi et al., 2018]). One neglected aspect of this complex picture is the role played by WtE plants' ownership. The institutional setting is rather diverse, internationally. In Germany there is a mix of both local and private ownership solutions. In Denmark most incinerators are owned by local authorities; in Sweden private, listed firms control the largest and more efficient WtE plants, with the decisions on their size taken either at the national or municipal government level. Municipalities hold minority stakes of Italian formally private utilities that run the largest incinerators, whereas a municipally controlled firm runs Austria's major WtE plants too, including Wien's Spittelau landmark incinerator. The main research question of our study is therefore to assess whether and how plant ownership and waste mobility interact in affecting recycling efforts, energy recovery and other equilibrium outcomes. In our simplified two-region setting, we analyse the role that plant ownership and key waste-policy measures, such as mobility, play in influencing equilibrium environmental damage and welfare. The two regions are identical but for the presence of waste-disposal facilities operating in each region: a WtE plant in Region 1, and a landfill dump in Region 2. We show that the institutional and ownership setting of WtE facilities (whether managed by the local government or run by independent private companies) should be carefully considered in designing optimal WtE policies. Ownership affects the quantity to be burned, the level of profit and its allocation among regions. If the local community owns the WtE plant, the combined effect of negative local externalities of waste disposal and its flows, the substitution of fossil fuels for heat and electricity generation as well as the profit are all internalized to determine the optimal quantity to be burned. In

[1] https://sweden.se/nature/the-swedish-recycling-revolution/

[2] See https://www.theguardian.com/sustainable-business/exporting-waste-uk-recyling-resource-scarcity-energy-security

contrast, private ownership does not necessarily take into account all these elements. We demonstrate that allowing for waste mobility across Regions leads to an equilibrium outcome that is both globally efficient and Pareto improving for the two Regions, but only if the local government owns the plant. Conversely, with no mobility the institutional setting is uninfluential, as long as the owner of the WtE plant acts as price-taker. The paper is organised as follows. In Section 2 we introduce the basic features of our model, in Section 3 we present the results for the case of a autarky. This assumption is relaxed in Section 4, where the results of the two models are compared. Section 5 concludes

2 The model

We use a simple two-region model to study the effects of waste disposal on environmental protection and welfare. The country is divided into two local jurisdictions or regions, 1 and 2, identical in everything but waste disposal. We assume that Region 1 has a WtE plant to dispose waste while Region 2 owns and manages a landfill site. Income generates an amount of waste equal to W_i, which can be disposed of in the same region i, it can be exported to the other, or it can be recycled. In line with the EU guidelines on waste management, Region 1 cannot send waste to Region 2 to be landfilled since it can be locally incinerated. With these assumptions, we can write:

$$\begin{aligned} W_1 &= q_1 + R_1 \qquad (1) \\ W_2 &= q_2 + R_2 + d_2 \end{aligned}$$

where q_i is the quantity of waste from Region i that is incinerated in Region 1, R_i is the quantity of waste recycled by Region i and d_2 is the quantity of waste produced and landfilled in Region 2. Since W_i is given, we take quantities q_1, q_2 and R_2 as decision variables:

$$R_1 = W_1 - q_1, \qquad d_2 = W_2 - q_2 - R_2.$$

Recycling R_i involves a monetary cost, quadratic in the quantity recycled: $\frac{c}{2}(R_i)^2$; this is the only form of waste use that does not produce any environmental damage. Each region requires an amount of energy E_i which can be produced either through non-renewable resources, or by a WtE plant. Energy obtained through non-renewable resources depletes the environmental endowment at a rate g. The energy produced by the WtE plant is equal to $z(q_1+q_2)$ and is sold at price p_E. In this process, the quantity $s(q_1+q_2)$ of ashes is created; it has to be disposed of at a price equal to m_c. Incineration produces two types of environmental cost: a) reduction in the quality of the environmental good because of combustion, which we assume to be quadratic in the quantity incinerated, and b) environmental damage due to the disposal of ashes, which can only be landfilled. The total environmental damage can be written as $\frac{v}{2}(q_1+q_2)^2$. Waste disposal through landfill dumping causes a reduction in the environmental good that is quadratic in the quantity landfilled ($\frac{k}{2}{d_2}^2$), and a monetary cost proportional to the quantity landfilled ($m_d d_2$). The initial endowment of the environmental good in Region i is A_i; its reduction in Region 1 depends on the combined effect of the following activities:

- energy production from sources other than waste, which amounts to $g(E_1 - z(q_1+q_2))$;
- the incineration of waste, including ashes disposal, through the term $\frac{v}{2}\left(q_1+q_2\right)^2$.

In Region 2 it depends on:

- energy production from sources other than waste, which amounts to gE_2;
- landfilling of d_2, through the term $\frac{k}{2}(d_2)^2 = \frac{k}{2}(W_2 - q_2 - R_2)^2$.

Finally, t represents the unit cost related to moving waste between the regions; it is assumed to be linear in the quantity transferred.

The incineration plant can be run either by the LA in Region 1 or it can be managed by a private firm. In both cases, it is assumed to be a profit-maximising firm. Its revenue is the sum of the value of the energy sold and the disposal fee that regions pay:

$$R_q = p_E z\left(q_1+q_2\right) + p_1 q_1 + p_2 q_2$$

where p_1 and p_2 are the unit prices paid by Region 1 and Region 2 to incinerate their waste. The WtE technology cost is quadratic in the quantity incinerated and linear in quantity of ashes to be disposed:

$$C_q = \frac{f}{2}(q_1+q_2)^2 + m_c s(q_1+q_2)$$

The profit of the incinerator is equal to:

$$\Pi = p_E\, z\,(q_1+q_2) + p_1\, q_1 + p_2\, q_2 - \frac{f}{2}(q_1+q_2)^2 - m_c\, s\,(q_1+q_2).$$

The welfare function is a linear combination of the utility of the environmental good, the cost of disposal and recycle and (if applicable) the profit of the WtE plant:

$$\begin{aligned} V_1 &= b\left(A_1 - g\,(E_1 - z\,(q_1+q_2)) - \frac{v}{2}(q_1+q_2)^2\right) - \frac{c}{2}(W_1-q_1)^2 - p_1\, q_1 + \delta\,\Pi(q_1,q_2). \quad (2)\\ V_2 &= b\left(A_2 - g\,E_2 - \frac{k}{2}\,(W_2 - q_2 - R_2)^2\right) - \frac{c}{2}R_2^2 - m_d\,(W_2 - q_2 - R_2) - (p_2+t)\,q_2. \end{aligned}$$

where b measures the preference for the environmental good and δ is the share of profit of the WtE plant that is distributed locally. We assume $\delta = 1$ if the LA owns the incinerator.

This framework allows us to study the effects of the decision to let each region to separately determine its level of waste-reducing effort, the implications for treating imported waste, and the role of institutional and market settings. In order to simplify and compare the different solutions, we assume that $W_1 = W_2 = W$.

2.1 First Best

In the classical regulation problem, the benevolent regulator would maximise welfare, defined as the sum of the regions' welfare function and the profit of the WtE plant. With the aim of comparing results under alternative scenarios, we calculate here the (internal) optimal conditions for a central planner wishing to optimise the sum of the welfare functions for both regions and the plant profit. The optimisation problem can be written as:

$$
\begin{aligned}
\text{Max}_{q_1,q_2,R_2}\; & b\left(A_1 - g\left(E_1 - z\left(q_1+q_2\right)\right) - \frac{v}{2}(q_1+q_2)^2\right) - \frac{c}{2}(W-q_1)^2 - p_1\,q_1 \\
& + b\left(A_2 - g\,E_2 - \frac{k}{2}\left(W-q_2-R_2\right)^2\right) - \frac{c}{2}R_2^2 - m_d\left(W-q_2-R_2\right) - \left(p_2+t\right)q_2 \\
& + p_E\,z\left(q_1+q_2\right) + p_1\,q_1 + p_2\,q_2 - \frac{f}{2}(q_1+q_2)^2 - m_c\,s\left(q_1+q_2\right) \\
\text{s.t.}\quad & q_1 \geq 0,\; W-q_1 \geq 0 \\
& q_2 \geq 0,\; R_2 \geq 0,\; W-q_2-R_2 \geq 0.
\end{aligned}
\tag{3}
$$

The F.O.C.s for the above problem are:

$$
\begin{cases}
b\left(g\,z - v\left(q_1+q_2\right)\right) + c\left(W-q_1\right) + p_E\,z - f\left(q_1+q_2\right) - m_c\,s = 0 \\
b\left(g\,z - v\left(q_1+q_2\right)\right) + p_E\,z - f\left(q_1+q_2\right) - m_c\,s + b\,k\left(W-q_2-R_2\right) + m_d - t = 0 \\
b\,k\left(W-q_2-R_2\right) - c\,R_2 + m_d = 0.
\end{cases}
\tag{4}
$$

The optimal solution for the quantity to be incinerated (q_i^{FB}), for recycling (R_i^{FB}), and for landfilling (d_2^{FB}) can be written as:

$$
\begin{aligned}
q_1^{FB} &= W - \frac{bk\left[2\left(bv+f\right)W - \left(p_E z - m_c s + bgz\right)\right] - \left(t - m_d + t\frac{bk}{c}\right)\left(bv+f\right)}{\left(bv+f+c\right)bk + \left(bk+c\right)\left(bv+f\right)} \\
q_2^{FB} &= W - \frac{\left(bk+c\right)\left[2\left(bv+f\right)W - \left(p_E z - m_c s + bgz\right)\right] + \left(t - m_d + t\frac{bk}{c}\right)\left(bv+f+c\right)}{\left(bv+f+c\right)bk + \left(bk+c\right)\left(bv+f\right)} \\
R_1^{FB} &= \frac{2Wbk\left(bv+f\right) - bk\left(bgz + p_E z - m_c s\right) + \left(m_d - \frac{tbk}{c}\right)\left(bv+f\right) - t\left(bv+f\right)}{\left(bv+f+c\right)bk + \left(bk+c\right)\left(bv+f\right)} \\
R_2^{FB} &= \frac{2Wbk\left(bv+f\right) - bk\left(bgz + p_E z - m_c s\right) + \left(m_d + \frac{tbk}{c}\right)\left(bv+f\right) + tbk}{\left(bv+f+c\right)bk + \left(bk+c\right)\left(bv+f\right)} \\
d_2^{FB} &= \frac{2Wc\left(bv+f\right) - c\left(bgz + p_E z - m_c s\right) + \left(bv+f+c\right)\left(t - 2m_d\right) + cm_d}{\left(bv+f+c\right)bk + \left(bk+c\right)\left(bv+f\right)}
\end{aligned}
\tag{5}
$$

The first two lines of Equation (5) show that in the First Best (FB) solution Region 1 incinerates more and recycles less than Region 2. This results is in line with what expected: for Region 2 incineration is costlier due to transport costs. Both regions decide to incinerate up

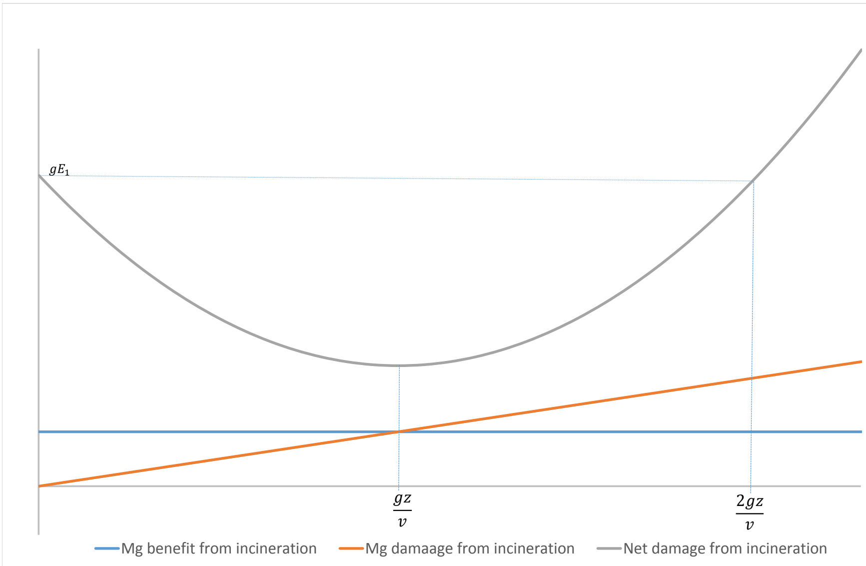


Figure 3: Damage

to the point where the price of incineration equals the marginal cost of available alternatives. The cost function for recycling is the same in the two Regions, but the price of alternatives in 2 is higher (otherwise Region 2 would not send waste to 1 in equilibrium) hence it recycles more.

We can solve for the environmental damage in the two regions by substituting the optimal quantities in equation (5) back in the objective function. Incineration produces two effects: a linear benefit represented by the reduction in the use of the natural resorce, $g\left(E_1 - z\left(q_1 + q_2\right)\right)$, and a negative, quadratic cost $\frac{v}{2}(q_1 + q_2)^2$. In Figure 3 we plot these functions.

On the horizontal axis we measure the quantity incinerated while on the vertical axis we measure the environmental costs and benefits deriving from incineration. The blue line represents the marginal benefits from incineration (gz) arising from the reduction in the use of non-renewable energy; the orange line represents the marginal environmental damage produced by incineration $(v(q_1 + q_2))$. The grey curve is the net environmental damage $g\left(E_1 - z\left(q_1 + q_2\right)\right) + \frac{v}{2}(q_1 + q_2)^2$. gE_1 is the quantity of natural resources that would be used to produce energy from non-renewable sources in the absence of a WtE techology. An increase in $(q_1 + q_2)$ causes at first a reduction in the environmental damage, because the marginal benefits are higher than the cost. However, as $q_1 + q_2$ rises, the damage increases to the point where it outweighs the benefits. The curve has a minimum for $q_1 + q_2 = \frac{gz}{v}$, the point where the marginal environmental benefits from incineration are equal to the marginal costs. Another interesting result emerges from Figure 3. For $q_1 + q_2 = \frac{2gz}{v}$, the environmental damage of incineration is equal to benefits and the stock of natural resource reduces to $A_1 - g\,E_1$. This is the maximum stock that can be preserved in a Region with landfill disposal and 100% recycling. This implies that if $q_1 + q_2 \leq \frac{2gz}{v}$ the environmental damage in Region 1 is certainly lower than in Region 2.

When costs and benefits of the WtE technology are duly considered, the optimal quantity to be incinerated is equal to

$$q_1^{FB} + q_2^{FB} = \frac{(2bk + c)\,(p_E z - m_c s + bgz) + c\,(m_d - t) + 2Wbkc - bkt}{(bv + f + c)\,bk + (bk + c)\,(bv + f)}$$

while the quantity of waste that would minimise the environmental damage is equal to $q_1 + q_2 = \frac{gz}{v}$. These quantities are equal only if

$$v = v^* := \frac{g\,z\,(b\,c\,k + 2\,b f k + c\,f)}{b\,k\,(2Wc - t) + (2\,b\,k + c)\,(p_E\,z - m_c\,s) + c\,(m_d - t)}. \tag{6}$$

.For $v < v^*$ (the environmental damage related to incineration is “sufficiently small”) the environmental damage is not minimised because the quantity of waste incinerated is too low. On the other hand when the environmental damage is “sufficiently high” $(v > v^*)$ the quantity of waste incinerated is too high.

In what follows we derive the optimal waste disposal policy of both regions, in a context where mobility is not allowed. In this setting, we analyse the equilibrium outcomes for the case where the WtE plant is owned by the LA and for when it is run privately. Next, we will relax the no mobility assumption and we will study the effect of this policy.

3 Waste autarky

When waste waste mobility is not allowed (i.e. $q_2 = 0$), Region 1 can choose between incineration and recycle, while Region 2 has the option of landfill or recycle. In this context, we study the effects of ownership on the optimal quantity to be incinerated.

Region 2 optimisation problem Let us first examine the optimal policy for Region 2, which sets the quantity R_2 that has to be recycled by solving:

$$\begin{aligned} \text{Max}_{R_2 \geq 0} \quad & b\left(A_2 - g\,E_2 - \frac{k}{2}(W - R_2)^2\right) - \frac{c}{2}R_2^2 - m_d(W - R_2) \\ \text{s.t.} \quad & W - R_2 \geq 0. \end{aligned} \tag{7}$$

The F.O.C. for the above problem is:

$$(-b\,k - c)\,R_2 + b\,k\,W + m_d = 0; \tag{8}$$

Provided that $m_d \leq c\,W$, an internal solution exists and can be written as[3]:

$$R_{2,nm} = \frac{W\,b\,k + m_d}{b\,k + c}, \quad d_{2,nm} = \frac{c\,W - m_d}{b\,k + c}. \tag{9}$$

Region 1 optimisation problem For Region 1 we consider two cases. In the first one, the WtE plant is owned by the local authority, which set the strategic choices of the incinerator and receives the plant's profits ($\delta = 1$). In the second case, the incinerator acts as a third party: the LA may participate to its profits, but it does not take any managerial decision, and the incineration fees are determined by market-clearing conditions. Optimal quantities in the two cases will be denoted by a superscript R (first case) or I (second case). The subscript nm stands for "no mobility".

LA owns the WtE plant In determining the optimal quantity to be incinerated, the local community takes into account the benefits from incineration, which are represented by: 1) the reduction in the use of non-renewable energy; 2) the net revenues from incineration; 3) the opportunity cost of recycling; 4) the costs (monetary and in terms of pollution) of such activities. Region 1 solves the following optimisation problem:

$$\begin{aligned} \text{Max}_{q_1 \geq 0} \quad & = b\left(A_1 - g\,(E_1 - z\,q_1) - \frac{v}{2}\,q_1^2\right) - \frac{c}{2}(W - q_1)^2 + p_E\,z\,q_1 - \frac{f}{2}q_1^2 - m_c\,s\,q_1, \\ \text{s.t.} \quad & W - q_1 \geq 0. \end{aligned}$$

[3] See Appendix A for a formal proof.

The F.O.C. for the above problem is:

$$(-b\,v - c - f)\,q_1 + b\,g\,z + c\,W - m_c\,s + p_E\,z = 0, \tag{10}$$

Provided that $b\,g\,z + p_E\,z - W\,(b\,v + f) \leq m_c\,s \leq b\,g\,z + W\,c + p_E\,z$, the following internal solution for the quantity to be incinerated can be defined:

$$q^R_{1,nm} = \frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f}. \tag{11}$$

Region 1 therefore recycles the following amount of waste:

$$R^R_{1,nm} = \frac{(b\,v + f)\,W - b\,g\,z + m_c\,s - p_E\,z}{b\,v + c + f} \tag{12}$$

LA does not own the WtE plant In this case, we consider a framework where the plant is owned by a private firm that sets the quantity of waste to be incinerated with the aim to maximise its profit. The firm is a price taker, the price is determined by market-clearing conditions. Region 1 loses its ability to control the amount of waste to be incinerated. The quantity q_1 and the price p_1 are obtained by equating demand and supply on the market. The WtE plant maximises surplus, i.e.:

$$\Pi = p_E\,z\,q_1 + p_1\,q_1 - \frac{f}{2}\,q_1^2 - m_c\,s\;q_1$$

while Region 1 optimises:

$$b\left(A_1 - g\,(E_1 - z\,q_1) - \frac{v}{2}\,q_1^2\right) - \frac{c}{2}(W - q_1)^2 - p_1\,q_1 + \delta\left(p_E\,z\,q_1 - \frac{f}{2}q_1^2 - m_c\,s\,q_1\right)$$

with some $\delta \in [0, 1)$. The optimal q_1 and p_1 are found by solving the system:

$$\begin{cases} -f\,q_1 - m_c\,s + p_E\,z + p_1 = 0, \\ (-b\,v - c)\,q_1 + b\,g\,z + c\,W - p_1 + \delta(-f\,q_1 - m_c\,s + p_E\,z + p_1) = 0. \end{cases} \tag{13}$$

The candidate solution is given by:

$$
\begin{aligned}
q_{1,nm}^{I} &= \frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f}, \\
p_{1,nm} &= \frac{b\,f\,g\,z + b\,m_c\,s\,v - b\,p_E\,v\,z + W\,c\,f + c\,m_c\,s - c\,p_E\,z}{b\,v + c + f}. \\
&= f q_{1,nm}^{I} - (p_E z - m_c s).
\end{aligned} \tag{14}
$$

3.1 Analysis

The results presented above show what happens under waste autarky. In Region 2, the quantity recycled is always positive, i.e. it is never optimal to landfill all the waste generated. On the other hand, no landfill (100% recycling) would be viable, provided that the marginal cost to recycle is lower than the (marginal) cost to landfill. It is interesting to note that, while in the internal solution the quantity of waste to be landfilled depends on the environmental damage, the conditions for a corner solution (100% recycling) depend only on private costs. By comparing equation (8) with equation (4) we can also assess that, provided an internal solution exists, $R_{2,nm} > R_{2,}^{FB}$ i.e. without waste mobility Region 2 recycles more than in FB. On the other hand, Region 1 recycles less than in FB (compare Equation (12) with Equation (4)). The intuition for this result is that without mobility, Region 1 equates the marginal cost of incinerating and the marginal cost of recycling; Region 2 equates the marginal cost of recycling with the marginal cost of landfilling. The latter is higher than with incineration (both because of the different environmental impact and because of energy production). This implies that the marginal cost in Region 2 is higher than in Region 1. The First Best, where mobility is allowed, requires incinerating some of the waste of Region 2. In order to keep the equality of marginal costs in Region 1, the amount of recycling in Region 1 must increase in FB.

When mobility is not allowed the quantity incinerated is independent from the institutional configuration of the WtE: the optimal quantity of waste sent to incineration is in fact the same (see Equations (11) and (14)). This is because even if the WtE is autonomous, the LA in Region 1 still controls the quantity incinerated through its recycling choices. This will no longer be the case when mobility is allowed, as shown below.

Finally, it is interesting to note that δ, the share of WtE profits that are locally distributed, does not influence the optimal quantities, which would be therefore the same also for $\delta = 0$. This has important policy implications: in autarky institutional settings rather than profit distribution matters: once Region 1 loses full control on the quantity incineated locally, the amount of profit distributed is no longer relevant in determining its reaction function and the quantity of waste to incinerate (q_1).

Environmental damage Let us now examine the welfare implications of the autarky regime by comparing the environmental damage in the two solutions. Given that the ownership of the WtE plant does not affect decisions on the quantity of waste to be incinerated, the comparison will simply be done between Region 1 and Region 2.

For Region 1, the environmental damage is given by the reduction in the environmental good A due to waste disposal, net of the saving due to energy production. The loss is weighted by b, the preferences for the environmental good, and can be written as:

$$b\left(gE - \frac{(b\,g\,z + W\,c - m_c\,s + p_E\,z)(-b\,g\,v\,z + W\,c\,v - 2\,c\,g\,z - 2\,f\,g\,z - m_c\,s\,v + p_E\,v\,z)}{2(b\,v + c + f)^2}.\right)$$

For Region 2 the damage is represented by the reduction in utility caused by the landfill-related damage and by the depletion of natural resources used to produce energy:

$$b\left(gE + \frac{k(c\,W - m_d)^2}{2\,(b\,k + c)^2}\right)$$

The second expression is always higher than the first one: in spite of the greater effort (and cost) in the recycling activity, the environmental damage in Region 2 is always higher than in Region 1.

4 Equilibrium with mobility of waste

Let us now relax the assumption that waste has to be disposed of in the region where it is produced. In principle, waste flows would be possible in both directions: from 1 to the landfill in 2 and from 2 to the WtE plant in 1. However, in the light of the discussion in Section 2, we assume that waste cannot be moved from Region 1 to Region 2 to be landfilled.

Region 2 optimisation problem As before, let us first examine the optimisation problem for Region 2. The problem can be written as:

$$\begin{aligned}\text{Max}_{q_2 \geq 0,\, R_2 \geq 0} \quad & b\left(A_2 - g\,E_2 - \frac{k}{2}(W - q_2 - R_2)^2\right) - \frac{c}{2}R_2^2 - m_d(W - q_2 - R_2) - (p_2 + t)\,q_2, \\ \text{s.t.} \quad & W - q_2 - R_2 \geq 0.\end{aligned}$$

The waste disposal choices of Region 2 can be written as:

$$\begin{aligned} R_2^M &= \frac{p_2 + t}{c} \\ q_2 &= W - \frac{p_2 + t}{c} - \frac{p_2}{b\,k} + \frac{m_d - t}{b\,k} \\ d_2^M &= \frac{p_2}{b\,k} - \frac{m_d - t}{b\,k} \end{aligned} \tag{15}$$

which has an internal solution only if $m_d < p_2 + t$ and $p_2 < c\frac{bkW+m_d}{bk+c} - t$, otherwise d_2 and/or q_2 are equal to 0. It is interesting to note that for $p_2 \geq c\frac{bkW+m_d}{bk+c} - t$, $R_2^M = \frac{bmW+m_d}{bk+c}$, which means that $R_2^{NM} > R_2^M$ i.e. mobility reduces the incentives to recycle in Region 2. On the other hand, when $m_d > p_2 + t$ the quantity recycled does not change while $q_2 = W - \frac{p_2+t}{c}$. The choices of Region 2 depends on the incineration price p_2, not on the ownership of the WtE plant. For Region 1 this element is instead relevant. Let us now examine the optimal decision for Region 1.

Region 1 optimisation problem If the LA in Region 1 controls the WtE facility, its objective is to maximise welfare with respect to q_1 and q_2 . In this way, it takes into account both the profit of the WtE plant and the costs deriving from waste disposal. When the WtE plant is privately owned, Region 1 will simply have to choose how much waste to incinerate and recycle.

LA in Region 1 owns WtE plant. In this case, the problem can be written as:

$$\begin{aligned} \text{Max}_{q_1 \geq 0,\, q_2 \geq 0} V_1 = \quad & b\left(A_1 - g\left(E_1 - z\left(q_1 + q_2\right)\right) - \frac{v}{2}\left(q_1 + q_2\right)^2\right) - \frac{c}{2}(W - q_1)^2 \\ & + p_E\, z\left(q_1 + q_2\right) + p_2\, q_2 - \frac{f}{2}(q_1 + q_2)^2 - m_c\, s\left(q_1 + q_2\right), \\ \text{s.t.} \quad & W - q_1 \geq 0. \end{aligned}$$

The solution is:

$$\begin{aligned} q_1 &= W - \frac{p_2}{c} \\ q_2 &= \frac{b\, g\, z - m_c\, s + p_E\, z}{b\, v + f} + \frac{p_2}{c} + \frac{p_2}{b\, v + f} - W. \\ R_1 &= \frac{p_2}{c} \end{aligned} \tag{16}$$

which is feasible if $p_2 \leq c\, W$. The total quantity incinerated is equal to $q_1 + q_2 = \frac{bgz + p_E z + p_2 - m_c s}{bv + f}$. If we compare equation (14) with equation (15) we can easily determine that $R_{2,m} > R_1$.

The equilibrium between demand and supply is determined by the equilibrium price p_2^*, which can be written as

$$\hat{p}^R_{2,m} = \frac{b\, k\left[(b\, v + f)\,(2\, W\, c - t) - c\,(b\, g\, z - m_c\, s + p_E\, z)\right] + (b\, v + f)\, c\,(m_d - t)}{b\, k\,(2\, b\, v + c + 2\, f) + c\,(b\, v + f)}, \tag{17}$$

The following scheme reports the relevant quantities in all cases in which mobility foresees an internal solution:

$$m_d < \hat{p}^R_{2,m} + t \leq \frac{c(W\, b\, k + m_d)}{b\, k + c} \qquad \begin{cases} R^R_{2,m} = \frac{\hat{p}^R_{2,m} + t}{c} \\ d^R_{2,m} = \frac{\hat{p}^R_{2,m} + t - m_d}{b\, k} \\ q^R_{2,m} = W - R^R_{2,m} - d^R_{2,m} \end{cases} \qquad q^R_{1,m} = W - \frac{\hat{p}^R_{2,m}}{c} \tag{18}$$

and it corresponds to the FB in the case presented in equation 5.

LA in Region 1 does not own WtE plant In this case, the quantity to be incinerated is set in a competitive market where both regions decide how much they are prepared to incinerate and the plant sets the quantity it wants to receive. Market-clearing conditions determine the price for which demand equals supply. In this case Region 1 loses the control over the quantity that is going to be incinerated and it will have to adjust its demand for incineration by internalising the environmental costs and benefits of the waste shipped across regions. The F.O.C. for Region 1 is:

$$b\,(g\,z - v\,(q_1 + q_2)) + c\,(W - q_1) - p_1 + \delta\,(p_E\,z + p_1 - f\,(q_1 + q_2) - m_c\,s) = 0 \tag{19}$$

The objective of the WtE plant is obviously to maximise profit:

$$\mathrm{Max}_{q_1 \geq 0,\, q_2 \geq 0} \quad p_E\,z\,(q_1 + q_2) + p_1\,q_1 + p_2\,q_2 - \frac{f}{2}(q_1 + q_2)^2 - m_c\,s\,(q_1 + q_2),$$

thus the F.O.C.s for the incinerator are:

$$\begin{cases} p_E\,z + p_1 - f\,(q_1 + q_2) - m_c\,s = 0, \\ p_E\,z + p_2 - f\,(q_1 + q_2) - m_c\,s = 0. \end{cases} \tag{20}$$

The objective of Region 2 is the same as before and the reaction function is the one in Equation (16). Optimal prices and quantities have to satisfy Equations (20), (19) and (16). If Equation (20) holds, the last term in Equation (19) is zero, therefore optimal quantities do not depend on δ. Moreover, Equation (20) implies:

$$p_1 = p_2 = f\,(q_1 + q_2) + m_c\,s - p_E\,z \tag{21}$$

Substituting this relationship back into Equation (19), we obtain the following reaction function for Region 1:

$$q_1 = \frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f} - q_2 \frac{b\,v + f}{b\,v + c + f}. \tag{22}$$

Waste mobility induces Region 1 to incinerate less waste and increase recycling. Combining Equations (16), (21) and (22), the equilibrium prices for which an internal solution exists can be written as:

$$\hat{p}^I_{1,m} = \hat{p}^I_{2,m} = \frac{b\,k[f\,(b\,g\,z + 2W c - t) + (b\,v + c)\,(m_c\,s - p_E\,z)] + c\,f\,(m_d - t)}{b\,k\,(b\,v + c + 2\,f) + c\,f}, \tag{23}$$

The following scheme describes the conditions under which mobility is optimal as well as the related quantities:

$$\begin{cases} R^I_{2,m} = \dfrac{\hat{p}^I_{2,m} + t}{c} \\ d^I_{2,m} = \dfrac{\hat{p}^I_{2,m} + t - m_d}{b\,k} \\ q^I_{2,m} = W - R^I_{2,m} - d^I_{2,m} \end{cases}$$
$$q^I_{1,m} = \frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f} - q^I_{2,m}\frac{b\,v + f}{b\,v + c + f}, \tag{24}$$

if $\quad m_d < \hat{p}^I_{2,m} + t \leq \frac{c(W\,b\,k + m_d)}{b\,k + c}$.

.

4.1 Analysis

A straightforward comparison of the two institutional settings presented above is not possible because the solutions are quite convoluted. Some general conclusions can however be drawn by examining the quantity of waste incinerated and the environmental damage in the two regions.

If the LA in Region 1 owns the plant, the solution replicates the FB, i.e. mobility is preferred to the no mobility case from a social point of view (See Equation 18). Mobility reduces the recycling (and landfilling) effort in Region 2, increases recycling in Region 1 and produces a welfare improvement for both regions. In equilibrium, Region 2 still recycles more than Region 1, due to transport costs. However, this solution represents a Pareto improvement with respect to autarky because of a reduction in the environmental damage and in the cost for recyling.

For Region 1, the comparison is more complicated. In Region 1 welfare (defined as the sum of the environmental damage, the cost related to waste disposal activities and the profit of the WtE plant) is higher when mobility is allowed, but the environmental damage may be higher than in the no mobility case. This may happen because Region 1 sets the quantity to incinerate, but taking into account the environmental consequences of incineration and the profit made from selling energy. This way, a trade-off may emerge between profit and environmental protection.

When the WtE plant is not owned by the LA in Region 1, the quantity of waste to be incinerated is usually different from the FB solution.When the WtE palnt is not owned by th LA it does not takes into account the net environmental cost of incineration so that the price is set in order to equalise the private benefits (in terms of revenue from the sale of energy) with the private costs of incineration. In appendix (F.2), we show that only if $v = v^* := \frac{g\,z\,(b\,c\,k+2\,b\,f\,k+c\,f)}{b\,k\,(2W\,c-t)+(2\,b\,k+c)\,(p_E\,z-m_c\,s)+c\,(m_d-t)}$ the quantity of waste incinerated in the two settings coincides. Note that, from Equation (6), this is equivalent to requiring that the environmental damage is minimised. Thus, if $v < v^*$ the total quantity of waste used to produce energy is higher when Region 1 owns the plant, and also Region 2 incinerates more. Whenever $v > v^*$ the converse is true.[4]

It is interesting to note that when $v > v^*$, Region 1 has to reduce its use of the incinerator and to increase recycling. In this case the Region will become poorer from an environmental and a monetary point of view.

For these reasons, Region 1 may prefer autarky to mobility even if the latter maximises total welfare. The conditions for mobility to be preferred are presented in Appendix (F.2.1) and depend on the relative weight of several factors: marginal net environmental damage (v), the marginal cost of recycling (c), waste transport costs and the efficiency parameters of the WtE plant.

When the LA does not own the plant, even the condition $v = v^*$does not assure that mobility is preferred by Region 1. This solution, which minimises the environmental damage and secures the same equilibrium in both settings, may not be welfare improving if the LA in Region 1 does not own the WtE plant. Although $q^I_{1,m} + q^I_{2,m}$ minimises the environmental damage, Region 1 has to face higher costs both for recycling and for inceneration, which are not matched by an increase in the profit of the WtE plant. Only if a "sufficiently large" (see appendix (F.2.2)) fraction of the profit is distributed to Region 1, mobility in this special case will be prefered.

5 Conclusions and directions for future research

The results presented above show that the institutional setting, defined as to which entity decides the quantity of waste to incinerate and its disposal price plays a very important role in determining how much waste the regions would prefer to ship for incineration or rather recycle locally. Let us first start with the case where mobility is not allowed. In this case, we

[4]See Appendix (F.2.1)

have shown that the quantity to be incinerated may be lower than what would be efficient, since it may not allow to reap the full net benefits of incineration. In this respect, the solution when the local authority owns the WtE plant and waste can be imported is superior, as it permits to reach a first-best allocation. However, welfare improvements in this case may not always imply a reduction in environmental damage: the outcome depends on the level of pollution generated by the WtE plant, which must be weighed against the benefits of the energy produced. On the other hand, the solution of a private WtE plant does not seem to be optimal. Since it would not fully take into account the (net) environmental consequences, the plant would incinerate too much/too little waste. However, this does not necessarily mean that both regions would be worse off in this setting. Due to the absence of environmental spillovers, Region 2 may be better off: this mainly depends on the waste disposal price that the WtE plant will ask. This is certainly one of the possible extensions of the baseline model. Another major problem to consider is the long-term duration of contracts that WtE plants are locked into. Incinerators and district heating systems have significant building costs and, to make a profit and repay investors, operators require a guaranteed stream of waste. The operators effectively engage with local authorities in contracts or deals that commit the latter to generating or importing a certain volume of waste over a long period of time, often 20 or 30 years. In addition, once local authorities build costly district heating systems, they come to rely on waste as a fuel commodity, making it hard to scale back to alternative sources of heat and power. In this respect, the model presented in this paper could be the first step towards a model that considers all these effects.

References

[Bank, 2018] Bank, W. (2018). Technical report, The World Bank Group, Washington.

[Cecere et al., 2014] Cecere, G., Mancinelli, S., and Mazzanti, M. (2014). Waste prevention and social preferences: the role of intrinsic and extrinsic motivations. *Ecological Economics*, 107:163 – 176.

[CEWEP, 2018] CEWEP (2018). Municipal waste treatment 2016. Technical report, Confederation of European Waste-to-Energy Plants.

[D'Amato et al., 2016] D'Amato, A., Mancinelli, S., and Zoli, M. (2016). Complementarity vs substitutability in waste management behaviors. *Ecological Economics*, 123:84 – 94.

[DEFRA, 2014] DEFRA (2014). Energy from waste. a guide to the debate. Technical report, Department for Environment, Food and Rural Affairs, UK Government.

[EEA, 2013] EEA (2013). Managing municipal solid waste. A review of achievements in 32 European countries. EEA Report 2/2013, European Environment Agency, Copenhagen.

[EEA, 2016] EEA (2016). More from less - material resources efficiency in europe. EEA Report 10/2016, European Environment Agency, Copenhagen.

[EPA, 2014] EPA (2014). Waste - resource conservation and recovery act (rca). Technical report, Environmental Protection Agency.

[EUCOMM, 2017a] EUCOMM (2017a). Report from the commission to the european parliament, the council, the european economic and social committe of regions on the role of waste-to-energy in the circular economy. Technical Report COM(2017)34 final, European Commission.

[EUCOMM, 2017b] EUCOMM (2017b). Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions on the implementation of the Circular Economy Action Plan. Technical Report COM(2017)33 final, European Commission.

[Eurostat, 2018] Eurostat (2018). Municipal waste statistics. statistics explained. Technical report, Eurostat, Bruxelles.

[Fredriksson, 2000] Fredriksson, P. (2000). The Siting of Hazardous Waste Facilities in Federal Systems: The Political Economy of NIMBY. *Environmental and Resource Economics*, 15(1):75–87.

[Levaggi et al., 2018] Levaggi, L., Levaggi, R., and Trecroci, C. (2018). Decentralisation and waste flows: A welfare approach. *Journal of Environmental Management*, 217:969 – 979.

[Persson and Münster, 2016] Persson, U. and Münster, M. (2016). Current and future prospects for heat recovery from waste in european district heating systems: A literature and data review. *Energy*, 110:116 – 128. Special issue on Smart Energy Systems and 4th Generation District Heating.

[Viscusi et al., 2011] Viscusi, W. K., Huber, J., and Bell, J. (2011). Promoting recycling: Private values, social norms, and economic incentives. *American Economic Review*, 101(3):65–70.

A Waste autarky: LA owns WtE plant

In the first case Region 1 has to solve the following optimisation problem:

$$\begin{aligned} \text{Max}_{q_1 \geq 0} \quad & b\left(A_1 - g\,(E_1 - z\,q_1) - \frac{v}{2}\,q_1^2\right) - \frac{c}{2}(W - q_1)^2 + p_E\,z\,q_1 - \frac{f}{2}q_1^2 - m_c\,s\,q_1, \\ \text{s.t.} \quad & W - q_1 \geq 0. \end{aligned}$$

The F.O.C. for the above problem is:

$$(-b\,v - c - f)\,q_1 + b\,g\,z + c\,W - m_c\,s + p_E\,z = 0,$$

which gives the following candidate for the maximum point:

$$q_{1,nm}^R = \frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f}. \tag{25}$$

The above solution is feasible only if the following condition is satisfied:

$$b\,g\,z + p_E\,z - W\,(b\,v + f) \leq m_c\,s \leq b\,g\,z + W\,c + p_E\,z.$$

In the subsequent analysis we will assume that the above condition is satisfied and thus that Region 1 in the no-mobility case recycles the following amount of waste:

$$R_{1,nm}^R = \frac{(b\,v + f)\,W - b\,g\,z + m_c\,s - p_E\,z}{b\,v + c + f}$$

and the environmental damage in Region 1 amounts to:

$$\frac{(b\,g\,z + W\,c - m_c\,s + p_E\,z)(-b\,g\,v\,z + W\,c\,v - 2\,c\,g\,z - 2\,f\,g\,z - m_c\,s\,v + p_E\,v\,z)}{2(b\,v + c + f)^2}.$$

B Waste autarky: LA does notowns WtE plant

In the second case the quantity q_1 and the price p_1 are obtained by equating demand and supply on the market. The objective of the WtE plant is to maximise:

$$p_E\,z\,q_1 + p_1\,q_1 - \frac{f}{2}\,q_1^2 - m_c\,s\;q_1$$

while Region 1 optimises:

$$b\left(A_1 - g\,(E_1 - z\,q_1) - \frac{v}{2}\,q_1^2\right) - \frac{c}{2}(W - q_1)^2 - p_1\,q_1 + \delta\left(p_E\,z\,q_1 - \frac{f}{2}q_1^2 - m_c\,s\,q_1\right)$$

with some $\delta \in [0, 1)$. This parameter does not influence the setting of the optimal quantities, that are therefore equal to the case $\delta = 0$; in fact the optimal q_1 and p_1 are found by solving the system:

$$\begin{cases} -f\,q_1 - m_c\,s + p_E\,z + p_1 = 0, \\ (-b\,v - c)\,q_1 + b\,g\,z + c\,W - p_1 + \delta(-f\,q_1 - m_c\,s + p_E\,z + p_1) = 0. \end{cases} \tag{26}$$

The candidate solution is given by:

$$\begin{aligned} q^I_{1,nm} &= \frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f}, \\ p_{1,nm} &= \frac{b\,f\,g\,z + b\,m_c\,s\,v - b\,p_E\,v\,z + W\,c\,f + c\,m_c\,s - c\,p_E\,z}{b\,v + c + f}. \end{aligned} \tag{27}$$

Comparing (25) with (27) we thus note that the property of the WtE does not affect the quantity of waste to be incinerated.

In this case the objective can be written as:

$$\begin{aligned} Max_{q_1}\,SW_1 &= b\left(A - gN_1 - \frac{v}{2}q_1^2\right) - \frac{c_1}{2}(R_1)^2 - m_1q_1 + \delta\left(\left(p_Ez + m_1\right)(q_1) - \frac{f}{2}(q_1)^2 - m_csq_1\right) \\ s.t \quad & R_1 = W - q_1 \\ & N_1 = E - zq_1 \end{aligned}$$

The constraints can be substituted back into the objective function. The FOC can be written as:

$$\begin{aligned} \frac{\partial}{\partial q_1} &: \left(b\left(A - g\,(E - zq_1) - \frac{v}{2}(q_1)^2\right) - \frac{c}{2}(W - q_1)^2 - m_1q_1 + \left(\left(p_Ez + m_1\right)(q_1) - \frac{f}{2}(q_1)^2 - m_cs(q_1)\right)\right) \\ &= bgz - bvq_1 + c\,(W - q_1) + p_Ez - fq_1 - m_cs \end{aligned}$$

and the optimal solution can be written as in the text.

C Mobility is allowed: LA controls WtE plant

Let us now analyse the case where mobility is allowed, i.e. $q_2 \geq 0$ in the two different settings. When Region 1 possesses the WtE plant, its objective is to optimise the welfare on both q_1 and q_2, since it also acts on the market:

$$\begin{aligned}
\mathrm{Max}_{q_1 \geq 0,\, q_2 \geq 0} \quad & b\left(A_1 - g\left(E_1 - z\left(q_1 + q_2\right)\right) - \frac{v}{2}\left(q_1 + q_2\right)^2\right) - \frac{c}{2}(W - q_1)^2 \\
& + p_E\, z\left(q_1 + q_2\right) + p_2\, q_2 - \frac{f}{2}(q_1 + q_2)^2 - m_c\, s\left(q_1 + q_2\right), \\
\text{s.t.} \quad & W - q_1 \geq 0.
\end{aligned}$$

Region 2 pursues instead the following objective:

$$\begin{aligned}
\mathrm{Max}_{q_2 \geq 0,\, R_2 \geq 0} \quad & b\left(A_2 - g\, E_2 - \frac{k}{2}(W - q_2 - R_2)^2\right) - \frac{c}{2}R_2^2 - m_d(W - q_2 - R_2) - (p_2 + t)\, q_2, \\
\text{s.t.} \quad & W - q_2 - R_2 \geq 0.
\end{aligned}$$

The F.O.C.s for Region 1 are:

$$\begin{cases} b(g\, z - v\left(q_1 + q_2\right)) + c\left(W - q_1\right) + p_E\, z - f\left(q_1 + q_2\right) - m_c\, s = 0, \\ b(g\, z - v\left(q_1 + q_2\right)) + p_E\, z + p_2 - f\left(q_1 + q_2\right) - m_c\, s = 0, \end{cases} \tag{28}$$

the F.O.C.s for Region 2 are:

$$\begin{cases} b\, k(W - q_2 - R_2) + m_d - p_2 - t = 0, \\ b\, k(W - q_2 - R_2) - c\, R_2 + m_d = 0. \end{cases} \tag{29}$$

It is easy to note that if conditions (28) are coupled with (29) the optimal quantities q_1, q_2 and R_2 have to satisfy (**??**), that is they coincide with the quantities of the First Best solution. From (28) we get $q_1 = W - \dfrac{p_2}{c}$, which is feasible if $p_2 \leq c\, W$. Depending on the price p_2 the supply is:

$$\frac{b\, g\, z - m_c\, s + p_E\, z}{b\, v + f} + \frac{p_2}{c} + \frac{p_2}{b\, v + f} - W.$$

From (29) the candidate optimal R_2 is $\dfrac{p_2+t}{c}$, which is feasible if $p_2+t \leq c\,W$, a stronger condition than the one above. Observing that it holds either $m_d \leq \frac{c(W\,b\,k+m_d)}{b\,k+c} \leq c\,W$ or $c\,W \leq \frac{c(W\,b\,k+m_d)}{b\,k+c} \leq m_d$, the demand is given by:

$$\begin{cases} W - \frac{p_2+t}{c} - \frac{p_2}{b\,k} + \frac{m_d-t}{b\,k}, & m_d \leq p_2+t \leq \frac{c(W\,b\,k+m_d)}{b\,k+c} \\ W - \frac{p_2+t}{c}, & p_2+t \leq \min\{c\,W, m_d\} \\ 0, & \text{otherwise.} \end{cases} \tag{30}$$

The price p_2 is obtained imposing the market clearing condition; the two candidate prices are:

$$\hat{p}^R_{2,m} = \frac{b\,k\,[(b\,v+f)\,(2\,W\,c-t) - c\,(b\,g\,z - m_c\,s + p_E\,z)] + (b\,v+f)\,c\,(m_d-t)}{b\,k\,(2\,b\,v+c+2\,f) + c\,(b\,v+f)}, \tag{31}$$

$$\bar{p}^R_{2,m} = \frac{(b\,v+f)\,(2Wc-t) - c\,(b\,g\,z - m_c\,s + p_E\,z)}{2b\,v+c+2f}. \tag{32}$$

The following scheme reports the relevant quantities in all cases in which mobility is optimal:

$$\text{if} \quad m_d < \hat{p}^R_{2,m} + t \leq \frac{c(W\,b\,k+m_d)}{b\,k+c} \qquad \begin{cases} R^R_{2,m} = \frac{\hat{p}^R_{2,m}+t}{c} \\ d^R_{2,m} = \frac{\hat{p}^R_{2,m}+t-m_d}{b\,k} \\ q^R_{2,m} = W - R^R_{2,m} - d^R_{2,m} \end{cases} \qquad q^R_{1,m} = W - \frac{\hat{p}^R_{2,m}}{c}$$

$$\text{if} \quad \bar{p}^R_{2,m} + t \leq \min\{c\,W, m_d\} \qquad \begin{cases} R^R_{2,m} = \frac{\bar{p}^R_{2,m}+t}{c} \\ d^R_{2,m} = 0 \\ q^R_{2,m} = W - \frac{\bar{p}^R_{2,m}+t}{c} \end{cases} \qquad q^R_{1,m} = W - \frac{\bar{p}^R_{2,m}}{c}$$

Since $\dfrac{W\,b\,k+m_d}{b\,k+c}$ is the quantity of waste recycled in absence of mobility, we can easily derive that less waste is recycled in Region 2 if mobility is allowed. Moreover, since

$$\frac{p_2+t-m_d}{b\,k} - \frac{c\,W-m_d}{b\,k+c} = \frac{(b\,k+c)(p_2+t) - b\,k\,c\,W - c\,m_d}{b\,k\,(b\,k+c)}$$

and mobility is optimal under the condition $p_2+t \leq \frac{c(W\,b\,k+m_d)}{b\,k+c}$, less waste is landfilled if mobility is allowed.

D Mobility is allowed: LA controls WtE plant

When Region 1 does not possess the incineration facility (but may participate to profits), its objective is to choose q_1 to maximise welfare:

$$\begin{aligned}
\text{Max}_{q_1 \geq 0} \quad & b\left(A_1 - g\,(E_1 - z\,(q_1+q_2)) - \frac{v}{2}\,(q_1+q_2)^2\right) - \frac{c}{2}(W-q_1)^2 - p_1\,q_1 \\
& + \delta\left(p_E\,z\,(q_1+q_2) + p_1\,q_1 + p_2\,q_2 - \frac{f}{2}(q_1+q_2)^2 - m_c\,s\,(q_1+q_2)\right), \\
\text{s.t.} \quad & W - q_1 \geq 0.
\end{aligned}$$

The F.O.C. for Region 1 is:

$$b\,(g\,z - v\,(q_1+q_2)) + c\,(W-q_1) - p_1 + \delta\,(p_E\,z + p_1 - f\,(q_1+q_2) - m_c\,s) = 0 \tag{33}$$

The objective of the WtE plant is obviously to maximise profit:

$$\text{Max}_{q_1 \geq 0,\, q_2 \geq 0} \quad p_E\,z\,(q_1+q_2) + p_1\,q_1 + p_2\,q_2 - \frac{f}{2}(q_1+q_2)^2 - m_c\,s\,(q_1+q_2),$$

thus the F.O.C.s for the incinerator are:

$$\begin{cases} p_E\,z + p_1 - f\,(q_1+q_2) - m_c\,s = 0, \\ p_E\,z + p_2 - f\,(q_1+q_2) - m_c\,s = 0. \end{cases} \tag{34}$$

The objective of Region 2 is the same as before and the reaction function is the one in (30). Optimal prices and quantities have to satisfy (34), (33) and (30). If (34) holds the last term in (33) is zero, therefore optimal quantities do not depend on δ. Moreover (34) implies:

$$p_1 = p_2 = f\,(q_1+q_2) + m_c\,s - p_E\,z \tag{35}$$

and plugging this relation in (33) the following reaction function for Region 1 is obtained:

$$q_1 = \frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f} - q_2\frac{b\,v + f}{b\,v + c + f}, \tag{36}$$

thus allowing mobility induces Region 1 to incinerate less waste and increase recycling. Combining (30), (35) and (36) the following candidate prices are derived:

$$\hat{p}^I_{1,m} = \hat{p}^I_{2,m} = \frac{b\,k[f\,(b\,g\,z + 2Wc - t) + (b\,v + c)\,(m_c\,s - p_E\,z)] + c\,f\,(m_d - t)}{b\,k\,(b\,v + c + 2\,f) + c\,f}, \tag{37}$$

$$\bar{p}^I_{1,m} = \bar{p}^I_{2,m} = \frac{f\,(b\,g\,z + 2Wc - t) + (b\,v + c)\,(m_c\,s - p_E\,z)}{b\,v + c + 2\,f}. \tag{38}$$

The following scheme describes the conditions under which mobility is optimal and the related quantities:

$$\text{if} \quad m_d < \hat{p}^I_{2,m} + t \le \frac{c(W b\,k + m_d)}{b\,k + c} \qquad \begin{cases} R^I_{2,m} = \dfrac{\hat{p}^I_{2,m} + t}{c} \\ d^I_{2,m} = \dfrac{\hat{p}^I_{2,m} + t - m_d}{b\,k} \\ q^I_{2,m} = W - R^I_{2,m} - d^I_{2,m} \end{cases}$$

$$\text{if} \quad \bar{p}^I_{2,m} + t \le \min\{c\,W, m_d\} \qquad \begin{cases} R^I_{2,m} = \dfrac{\bar{p}^I_{2,m} + t}{c} \\ d^I_{2,m} = 0 \\ q^I_{2,m} = W - \dfrac{\bar{p}^I_{2,m} + t}{c} \end{cases}$$

and in all cases:

$$q^I_{1,m} = \max\left\{\frac{b\,g\,z + W\,c - m_c\,s + p_E\,z}{b\,v + c + f} - q^I_{2,m}\frac{b\,v + f}{b\,v + c + f}, 0\right\}.$$

E Analysis

Let us now analyse the above results and compare the outcomes in the different frameworks.

Firstly, we examine the case where the WtE facility is owned by Region 1 and investigate the role of mobility. The optimal quantity q_1 of waste to be incinerated is obtained from (11). If we define the function φ as:

$$\varphi(q) = b\,(g\,z - q\,v) + c\,(W - q) - f\,q - m_c\,s + p_E\,z$$

we have

$$\varphi(q^R_{1,nm}) = 0, \qquad \varphi(q^R_{1,m}) = (b\,v + f)\,q^R_{2,m}$$

and since φ is decreasing in q Region 1 incinerates less waste (and thus recycles more) if mobility is allowed.

For Region 2 we already noticed that mobility decreases both the need to recycle and to landfill; moreover

$$R_{2,m} = \frac{p_2 + t}{c}, \qquad R_{1,m} = \frac{p_2}{c},$$

therefore Region 2 recycles more than Region 1. Since for Region 2 the environmental damage only depends on the landfilled quantity, mobility lowers also this quantity.

Moreover we have:

$$\varphi(q^R_{1,m} + q^R_{2,m}) = -c\,q^R_{2,m} \tag{39}$$

therefore the total quantity of waste to be incinerated is higher when mobility is allowed. The environmental damage in Region 1 is a convex, quadratic function of the total incinerated quantity; mobility increases the environmental damage whenever

$$\frac{q^R_{1,nm} + q^R_{1,m} + q^R_{2,m}}{2} > \frac{g\,z}{v}.$$

Suppose now that mobility is allowed and let us compare the effects of the ownership of the incinerator; we suppose that conditions for the existence of internal solutions are met. Substituting (35) in (33) and from (39) we have:

$$q^R_{2,m} = -\frac{1}{c}\varphi(q^R_{1,m} + q^R_{2,m}), \qquad q^I_{2,m} = -\frac{1}{c}\varphi(q^I_{1,m} + q^I_{2,m}), \tag{40}$$

therefore optimal quantities in the two models can be easily compared by studying the difference in the total incinerated quantity. Since relations between optimal quantities in the two cases are the same, the total quantities to be incinerated are equal only if prices are the same. Comparing the second equation in (28) with (35) prices in the two schemes are equal if and only if:

$$v\,\left(q^R_{1,m} + q^R_{2,m}\right) = gz; \tag{41}$$

this condition is satisfied only if:

$$v = v^* := \frac{g\,z\,(b\,c\,k + 2\,bfk + c\,f)}{b\,k\,(2Wc - t) + (2\,b\,k + c)\,(p_E\,z - m_c\,s) + c\,(m_d - t)}.$$

Note that (41) is equivalent to requiring that the environmental damage is at its minimum. Thus, if $v < v^*$ the total quantity of waste used to produce energy is greater when Region 1 owns the plant, which implies that Region 2 incinerates a greater quantity of waste and from (30) the price p_2 is lower than in the other case. Moreover, from (40), since $\varphi(x) - \varphi(y) = -(x-y)(bv + c + f)$ it is:

$$q^I_{1,m} - q^R_{1,m} = -\frac{bv + f}{bv + c + f}\,(q^I_{2,m} - q^R_{2,m})$$

therefore Region 1 incinerates less if it is the owner. With respect to the First Best solution, if $v < v^*$ and the WtE plant is not owned by Region 1 the total quantity of incinerated waste is less: Region 2 incinerates less, while Region 1 incinerates more. Whenever $v > v^*$ the converse is true. For $v = v^*$ the quantities in the two frameworks coincide with the ones of the First Best solution.

Let us now assume that Region 1 does not own the incinerator and compare the solutions where mobility is or is not allowed. Using the same notation as above, from (26) and (40) we have:

$$q^I_{1,nm} = \varphi^{-1}(0), \qquad q^I_{1,m} + q^I_{2,m} = \varphi^{-1}(-c\,q^I_{2,m})$$

therefore, since φ is decreasing and the same holds true for its inverse, if mobility is allowed more waste is incinerated. Moreover since $q^I_{1,m} = \varphi^{-1}(-c\,q^I_{2,m}) - q^I_{2,m}$ and

$$\frac{\mathrm{d}}{\mathrm{d}\,q}(\varphi^{-1}(c\,q) + q) = \frac{bv + f}{bv + c + f} > 0$$

it is $q^I_{1,m} < \varphi^{-1}(0) = q^I_{1,nm}$, thus the quantity of waste that Region 1 sends to the incinerator is lower if mobility is allowed. From (26) and (34) in both cases the price is increasing in the total quantity of incinerated waste, therefore the price is higher if mobility is allowed.

Defining

$$F(q) = b\left(gzq - \frac{v}{2}q^2\right) - \frac{c}{2}\left(W - q - \frac{1}{c}\varphi(q)\right)^2 - (fq + m_c s - p_E z)\left(q + \frac{1}{c}\varphi(q)\right)$$

the non-constant part of the welfare function for Region 1 can be written as $F(q^I_{1,nm})$ or $F(q^I_{1,m} + q^I_{2,m})$ resp. The above function is quadratic in q and by standard calculations:

$$c\,F'(q) = q\left(f^2 - bv\,(bv + c)\right) + (bv + f + c)\,(bgz - f q^I_{1,nm}).$$

Depending on the sign of $f^2 - bv\,(bv + c)$ the function is either convex, concave or linear. In the first two cases it has a critical point at

$$q_c = \frac{bv + c + f}{f^2 - bv\,(bv + c)}\,(f q^I_{1,nm} - bgz).$$

Since $q^I_{1,nm} < q^I_{1,m} + q^I_{2,m}$ mobility is welfare improving for Region 1 only in the following cases:

- $f^2 - bv\,(bv + c) > 0$ and $\frac{q^I_{1,nm} + q^I_{1,m} + q^I_{2,m}}{2} \geq q_c$;
- $f^2 - bv\,(bv + c) < 0$ and $\frac{q^I_{1,nm} + q^I_{1,m} + q^I_{2,m}}{2} \leq q_c$;
- $f^2 - bv\,(bv + c) = 0$ and $f\,q^I_{1,nm} \leq bgz$;

with indifference in case of an equality sign in the above expressions.

F Analysis

F.1 LA owns WtE

Let us examine the case where the WtE facility is owned by Region 1 and investigate the role of mobility. The optimal quantity q_1 of waste to be incinerated is obtained either from (10) or (28). If we define the function φ as:

$$\varphi(q) = b\,(g\,z - q\,v) + c\,(W - q) - f\,q - m_c\,s + p_E\,z$$

it is possible to write

$$\varphi(q^R_{1,nm}) = 0, \qquad \varphi(q^R_{1,m}) = (b\,v + f)\,q^R_{2,m}$$

Since φ is decreasing in q, Region 1 incinerates less waste (and thus recycles more) if mobility is allowed.

For Region 2 we can compare 9 with 18 to show that the quantity recycled decreases when mobility is allowed. From 9 $\dfrac{W b\, k + m_d}{b\, k + c}$ is the quantity of waste recycled in the absence of mobility and is also the quantity recycled if the price to incinerate is too high ($\hat{p}^R_{2,m} \geq \frac{c(W b\, k+m_d)}{b\, k+c} - t$). This implies that when an internal solution exists $R^R_{2,m} = \frac{\hat{p}^R_{2,m}+t}{c} < R^R_{2,nm} = W b\, k+m_d$which means that less waste is recycled in Region 2 if mobility is allowed. Moreover, since

$$\frac{p_2 + t - m_d}{b\, k} - \frac{c\, W - m_d}{b\, k + c} = \frac{(b\, k + c)(p_2 + t) - b\, k\, c\, W - c\, m_d}{b\, k\, (b\, k + c)}$$

and mobility is optimal under the condition $p_2 + t \leq \frac{c(W b\, k+m_d)}{b\, k+c}$, less waste is landfilled if mobility is allowed. Finally from 18 we can see that $R_{2,m} = \frac{p_2+t}{c}$, $\quad R_{1,m} = \frac{p_2}{c}$, $\quad$ therefore Region 2 recycles more than Region 1, i.e. allowing mobility, reduces the recycling effort in Region 2, increases latter in 1, but does not equalise the two.

Since for Region 2 the environmental damage only depends on the landfilled quantity, mobility reduces also this quantity, hence we can conclude that for Region 2 mobility is represents an improvement with respect to the no mobility case.

For Region 1, the comparison is more complicated. From a welfare point of view (defined as the sum of the environmetal damage, the cost related to waste disposal activities and the profit of the WtE plant, Region 1 is better off when mobility is allowed since they open to importing waste only if this option allows to improve their welfare. However, this does not necessarily means that the environment is protected by this solution. Opening to waste imports may allow to monetize the value of the enviroment through a reduction in its quality in exchange for a higher profit of the WtE plant.

Using the function φ defined above we can write:

$$\varphi(q^R_{1,m} + q^R_{2,m}) = -c\, q^R_{2,m} \tag{42}$$

therefore the total quantity of waste to be incinerated is higher when mobility is allowed. The environmental damage in Region 1 is a convex, quadratic function of the total innerated quantity; mobility increases the environmental damage whenever

$$\frac{q^R_{1,nm} + q^R_{1,m} + q^R_{2,m}}{2} > \frac{g\, z}{v}.$$

F.2 LA does not own the WtE plant

Let us now study the effects of the ownership of the incinerator when the conditions for the existence of internal solutions are met. Substituting (21) in (19) and from (42) we have:

$$q_{2,m}^{R} = -\frac{1}{c}\varphi(q_{1,m}^{R} + q_{2,m}^{R}), \qquad q_{2,m}^{I} = -\frac{1}{c}\varphi(q_{1,m}^{I} + q_{2,m}^{I}), \tag{43}$$

therefore optimal quantities in the two models can be easily compared by studying the difference in the total quantity incinerated which are equal in the two models only if prices are the same. Comparing the second equation in (28) with (21) prices in the two schemes are equal if and only if:

$$v\ \left(q_{1,m}^{R} + q_{2,m}^{R}\right) = gz. \tag{44}$$

This condition is satisfied only if:

$$v = v^* := \frac{g\,z\,(b\,c\,k + 2\,bfk + c\,f)}{b\,k\,(2Wc - t) + (2\,b\,k + c)\,(p_E\,z - m_c\,s) + c\,(m_d - t)}.$$

Note that (44) is equivalent to requiring that the environmental damage is at its minimum. Thus, if $v < v^*$ the total quantity of waste used to produce energy is greater when Region 1 owns the plant, which implies that Region 2 incinerates a greater quantity of waste and from (30) the price p_2 is lower than in the other case. Moreover, from (43), since $\varphi(x) - \varphi(y) = -(x-y)(bv + c + f)$ it is:

$$q_{1,m}^{I} - q_{1,m}^{R} = -\frac{bv + f}{bv + c + f}\,(q_{2,m}^{I} - q_{2,m}^{R})$$

therefore Region 1 incinerates less if it is the owner. With respect to the First Best solution, if $v < v^*$ and the WtE plant is not owned by Region 1 the total quantity of incinerated waste is less: Region 2 incinerates less, while Region 1 incinerates more. Whenever $v > v^*$ the converse is true. For $v = v^*$ the quantities in the two frameworks coincide with the ones of the First Best solution.

It is interesting to note that the prices in the two schemes are equal if and only if:

$$v\ \left(q_{1,m}^{R} + q_{2,m}^{R}\right) = gz; \tag{45}$$

Note that (45) is equivalent to requiring that the environmental damage is at its minimum.

Thus, if $v < v^*$ the total quantity of waste used to produce energy is greater when Region 1 owns the plant, which implies that Region 2 incinerates a greater quantity of waste and from (30) the price p_2 is lower than in the other case. Moreover, from (43), since $\varphi(x) - \varphi(y) = -(x-y)(bv+c+f)$ it is:

$$q^I_{1,m} - q^R_{1,m} = -\frac{bv+f}{bv+c+f}\,(q^I_{2,m} - q^R_{2,m})$$

F.2.1 Welfare comparison: mobility vs no mobility case

Let us now assume that Region 1 does not own the incinerator and compare the solutions where mobility is or is not allowed. Using the same notation as above, from (13) and (43) we have:

$$q^I_{1,nm} = \varphi^{-1}(0), \qquad q^I_{1,m} + q^I_{2,m} = \varphi^{-1}(-c\,q^I_{2,m})$$

therefore, since φ is decreasing and the same holds true for its inverse, if mobility is allowed more waste is incinerated. Moreover since $q^I_{1,m} = \varphi^{-1}(-c\,q^I_{2,m}) - q^I_{2,m}$ and

$$\frac{\mathrm{d}}{\mathrm{d}\,q}(\varphi^{-1}(c\,q) + q) = \frac{bv+f}{bv+c+f} > 0$$

it is $q^I_{1,m} < \varphi^{-1}(0) = q^I_{1,nm}$, thus the quantity of waste that Region 1 sends to the incinerator is lower if mobility is allowed. From (13) and (20) in both cases the price is increasing in the total quantity of incinerated waste, therefore the price is higher if mobility is allowed.

Defining

$$F(q) = b\left(gzq - \frac{v}{2}q^2\right) - \frac{c}{2}\left(W - q - \frac{1}{c}\varphi(q)\right)^2 - (fq + m_c s - p_E z)\left(q + \frac{1}{c}\varphi(q)\right)$$

the non-constant part of the welfare function for Region 1 can be written as $F(q^I_{1,nm})$ or $F(q^I_{1,m} + q^I_{2,m})$ resp. The above function is quadratic in q and by standard calculations:

$$c\,F'(q) = q\left(f^2 - bv\,(bv+c)\right) + (bv+f+c)\,(bgz - fq^I_{1,nm}).$$

Depending on the sign of $f^2 - bv\,(bv + c)$ the function is either convex, concave or linear. In the first two cases it has a critical point at

$$q_c = \frac{bv + c + f}{f^2 - bv\,(bv + c)}\,(f q^I_{1,nm} - bgz).$$

Since $q^I_{1,nm} < q^I_{1,m} + q^I_{2,m}$ mobility is welfare improving for Region 1 only in the following cases:

- $f^2 - bv\,(bv + c) > 0$ and $\frac{q^I_{1,nm}+q^I_{1,m}+q^I_{2,m}}{2} \geq q_c$;
- $f^2 - bv\,(bv + c) < 0$ and $\frac{q^I_{1,nm}+q^I_{1,m}+q^I_{2,m}}{2} \leq q_c$;
- $f^2 - bv\,(bv + c) = 0$ and $f\,q^I_{1,nm} \leq bgz$;

with indifference in case of an equality sign in the above expressions.

However, from this intuition we can infer that it may exist a level of profit for which Region 1 is better off with mobility even if the quantity incinerated is not optimal.

F.2.2 Optimal level of δ

Using equation ???? and substuting back the opimal price and quantities, we can write this optimal level as:

$$\delta = \frac{2Wq^I_{1,nm} - 2Wq^I_{1,m} + \left(q^I_{1,m}\right)^2 - \left(q^I_{1,nm}\right)^2}{f\left(q^I_{1,nm} + q^I_{1,m} + q^I_{2,m}\right)}c + \left(\frac{q^I_{1,nm} + q^I_{1,m} + q^I_{2,m}}{f}v - \frac{2gz}{f}\right)b + \frac{2\hat{p}^I_{1,m}q^I_{1,m} - 2p^I_{1,nm}q^I_{1,nm}}{f\left(q^I_{1,nm} + q^I_{1,m} + q^I_{2,m}\right)}$$