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Abstract

Electricity markets are increasingly integrated across borders, but transmission and renewable energy policies often remain local and uncoordinated. In this paper, we analyze how cooperative behavior in developing renewable energy technologies across borders and/or cross-border transmission capacity investment can reduce the cost of achieving a renewable energy target. We use a three step equilibrium model with: i) transmission investment, ii) generation investment and iii) electricity market that we apply to an interconnected two zone system. We find that it pays to cooperate if the zones have different renewable energy sources, but the success of a renewable energy cooperation also depends on cooperation in transmission development, which is therefore an important interaction to take into account in renewable energy policy discussions.

Keywords

Renewable energy; transmission network; electricity market; modeling

Introduction[*]

Since more than three decades, important institutional changes have impacted (and impact) the electricity sector. The liberalization process that started in the 90's, brought competition into the electricity industry and renewed interest in infrastructure regulation. Together with the electricity sector liberalization process, climate change and renewable energy policies have also been implemented in order to modify the way electricity is produced, using innovative technologies (Aune et al., 2008; Glachant and Lévêque, 2009).

In both the US and the EU, there are multi-zone electrical systems that have been interconnected before these institutional changes took place. Recently, some efforts have been made to coordinate electricity markets across these existing interconnections. In the EU, this has been driven by cooperation among market operators ("market coupling": Meeus et al., 2005; 2011a; 2011b), while in the US the approach has rather been to introduce regional market operators ("Regional Transmission Organization": Benjamin, 2007; Joskow, 2005). A similar coordination effort has not yet been made for the development of renewable energy technologies across borders and cross-border transmission capacity investment, but it is increasingly considered as larger scale renewable resources are being developed at larger distances from load centers.

Therefore, understanding whether it pays to cooperate in a multi-zone electrical system is a key issue for policy makers, but there are surprisingly few papers that have tried to model how cooperative behavior reduces the cost of achieving a renewable energy target. Aune et al. (2011) do model and compare cooperative and non-cooperative development of renewable energy across borders. The authors also apply their model to the EU, concluding that cooperative behavior would cut the cost of achieving the national renewable energy targets for 2020 by almost 70%. Buijs et al. (2011), Buijs and Belmans (2011) and Drondorf et al. (2010) demonstrate with numerical examples how non-cooperative transmission development across borders can lead to suboptimal investment. These papers did however not have the objective to investigate the interactions between transmission and generation investment decisions, while the work of Sauma and Oren (2006, 2009) emphasizes the importance of these interactions. Indeed, Aune et al. (2011) focuses on generation investment; and Buijs et al. (2011), Buijs and Belmans (2011) and Drondorf et al. (2010) model transmission investment for a fixed generation park.

The aim of this paper is to analyze how cooperative behavior in developing renewable energy technologies across borders and/or cross-border transmission capacity investment can reduce the cost of achieving a renewable energy target. We develop a three step equilibrium model to take into account the interactions between transmission and generation investment decisions with: i) transmission investment, ii) generation investment and iii) electricity market. We focus on a setting with two zones that are interconnected by a single transmission line. The two zones are identical, i.e. they have the same consumption profile, and equal access to electricity generation technologies with the same costs. We use a numerical example to demonstrate how the results change in more realistic cases with renewable energy sources that have different availabilities and/or that are negatively correlated.

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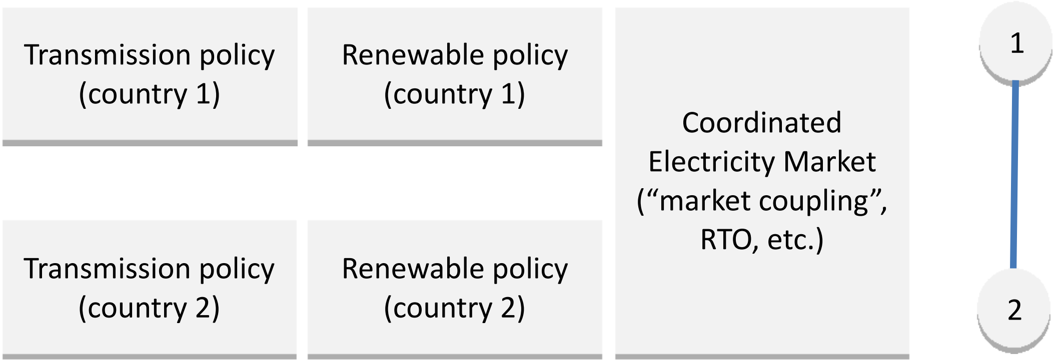
[*] We are grateful to Denny Ellerman for inviting us to the renewable energy modeling seminar of the climate policy unit he directs at the European University Institute in Florence, which has inspired us to work on this topic. We thank the discussants William D'haeseleer, Jean-Michel Glachant, Ignacio Perez Arriaga, Mario Ragwitz, Pippo Ranci, and Christian von Hirschhausen, and the seminar participants for their detailed comments. We also thank Patrik Buijs, Erik Delarue and Pedro Linares who have been kind to share their GAMS code, which has been our starting point to develop the model in this paper.

The paper is organized into 3 sections. Section 1 describes the different policy cases that are analyzed in the paper. Section 2 explains how these policy cases are modeled. Section 3 demonstrates how the model behaves with a numerical example.

1. Different policy cases: cooperative or non-cooperative

In this section, we describe the policy cases we will consider in our analysis (Figure 1, and Table 1).

Figure 1: two-zone electricity system



Three policy dimensions are considered in this paper: i) electricity market; ii) renewable energy policy; and iii) transmission policy.[1]

1.1 Electricity market

In our two zone setting, the electricity markets are perfectly coordinated. This means that there is perfect arbitrage between the two zones so that the zonal prices only diverge in moments of time where the transmission line is congested. In other words, the model calculates the locational marginal prices for the two-zone system.

1.2 Renewable energy policy

Today, renewable energy sources are typically non-competitive, i.e. their costs are higher than conventional generation technologies. Renewable development policies therefore provide public support to the development of these sources so that that they enter in the market. The public benefits are a reduction of emissions, future renewable cost reduction by learning processes, green jobs and renewable technology industry development. Renewable development policies have been implemented over the world using several instruments as green certificates system, feed in tariff or investment subsidies (Aune et al., 2008; Haas et al., 2011; IEA, 2009).

Renewable energy development policy across borders is limited in the US and the EU. Most states adopted provisions to ensure that local benefits or local RES targets, do not leak across the border to other states (Lund, 2009; Wiser, 2007; Yin and Powers, 2010). In our two-zone setting, the status quo is therefore that each zone has its own target to use renewable energy sources for part of the electricity it consumes, and the zones do not want this target to be achieved with renewable energy imports from the other zone. Cooperation then implies that the local targets that need to be achieved with local

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[1] Note that we do not model other climate change policies where member states are already cooperating, such as the European Emission Trading Scheme. First, it would not modify our main results of how cooperative behavior can improve welfare. Second, including this scheme would imply studying other policy interactions that are out of the scope of this paper, but have already been treated by for instance Linares et al (2008).

investment in renewable energy are replaced by a regional target that is the sum of the two local targets, and that is achieved with investment in renewable energy where it is cheapest. Cooperation also implies that the total cost of achieving the renewable energy target is shared by local consumers in proportion to their local target.

1.3 Transmission policy

Transmission development across borders is limited in the US and the EU. In the US context (Benjamin, 2007), there is a federal regulatory authority, but transmission investments are often decided locally. Even in the case of regions that have a Regional Transmission Organization (RTO), inter-state interconnections depend of local/state decisions as transmission investments are undertaken by transmission owners that are regulated by state regulatory authorities (Hirst, 2004; Joskow, 2005). In the EU context (Buijs et al., 2010), transmission development decisions are also taken locally and regulation is also local as there is no European regulator.

In our two-zone setting, the status quo is therefore that each zone invests in the single transmission line that interconnects them to maximize their own zonal welfare, and it does not take into account the impact on the welfare impact of the other zone. Cooperation then implies that the single transmission line interconnecting the two zones is expanded to maximize the total welfare in the two-zone electricity system.

Table 1: Matrix representation of the policy cases

		Cross-border renewable energy development	
		Non-cooperative	**Cooperative**
Cross-border transmission development	**Non-cooperative**	Status quo	Renewable energy cooperation
	Cooperative	Transmission cooperation	Full cooperation

2. Methodology to solve the policy cases

In order to study the interaction between renewable energy and transmission policy in a two-zone electrical system, we build a three-step equilibrium model. In this section, we discuss these three steps: i) transmission investment, ii) generation investment and iii) electricity market (production) in reverse order.

2.1 Electricity market

The third step of the model is where the electricity prices are determined. The prices are a result of the assumed demand, the production decisions of the generators in the model, and the market operator that makes sure that the electricity market is perfectly coordinated.

2.1.1 Demand

We use a multi-period model, and different time segment periods l can have a different duration t_l (measured in hours), so that a load duration curve can be included in the model, which is typically used in the electricity sector to represent a year of demand. The level of demand in zone n is $d_{l,n}$ (expressed in MW's).

Demand is inelastic, but the model includes the possibility of having shortages (i.e., demand can be higher than generation capacity). $z_{l,n}$ is the unsatisfied demand in time segment l (in MW) and in zone n. In hours which there are shortage cases, the price is fixed by the Value Of Lost Load ($VOLL$), being the economic value (in €/MWh) of unsatisfied electricity demand. $VOLL$ is often taken as a conventional value ranging between 1000 and 10 000 €/MWh.

Consumers maximize their surplus respecting the following equation:

Equation (1): $VOLL - ElectPrice_{l,n} > 0 \;\perp\; z_{l,n} > 0 \qquad \forall\, l,n$

Equation 1 ensures that in periods and zones with lost load ($z_{l,n}$ > 0), the electricity price has to be at least the value of lost load (VOLL), while the electricity price will be lower in periods that demand can be satisfied ($z_{l,n}$ = 0).

2.1.2 Generation

The model considers different types of generation technologies. There are s types of conventional generation technologies and r types of renewable energy technologies in each zone n. Technology types are generators that are modeled with a different constant marginal operating cost, which is $VC_{s,n}$ for the conventional generation technologies and $VCR_{r,n}$ for the renewable energy technologies (in €/MWh). In each period l, these generators produce a certain amount of electricity, which is $x_{l,s,n}$ and $xR_{l,r,n}$, respectively.

We assume a perfectly competitive electricity market where generators do not produce strategically to increase prices. Said differently, generators take the electricity price as an exogenous variable when they take production decisions. Indeed, generators bid their variables costs so that prices reflect the variable costs of the last plant that is needed to match demand. The production decision of conventional and renewable generators can then be expressed by the following equations:

Equation (2): $VC_{s,n} + y\_g_{l,s,n} - ElectPrice_{l,n} > 0 \;\perp\; x_{l,s,n} > 0 \qquad \forall\, l,s,n$

Equation (3): $VCR_{r,n} + y\_gR_{l,r,n} - ElectPrice_{l,n} > 0 \;\perp\; xR_{l,r,n} > 0 \qquad \forall\, l,r,n$

Equation (4): $g_{s,n} - x_{l,s,n} > 0 \;\perp\; y\_g_{l,s,n} > 0 \qquad \forall\, l,s,n$

Equation (5): $aR_{l,r,n} * gR_{r,n} - xR_{l,r,n} > 0 \;\perp\; y\_gR_{l,r,n} > 0 \qquad \forall\, l,r,n$

Equations 2 and 3 ensure that in periods where a conventional and renewable generator produces ($x_{l,s,n}$, $xR_{l,r,n}$ >0), the electricity price is high enough to cover the generator's variable cost, while the electricity price can be lower in periods that the generator does not produce ($x_{l,s,n}$, $xR_{l,r,n}$ = 0).

Equations 4 and 5 ensure that production always respects the renewable and conventional generation capacity constraints. For the case of conventional generation (equation 4), generation capacity constraint means that production should always be equal or less than installed generation capacity. We suppose that conventional capacity is 100% available over the year (i.e., no need to stop for maintenance). For the case of renewable generation (equation 5), installed capacity is adjusted by an availability factor ($aR_{l,r,n}$) that depend on the type of technology, the zone and the segment period of production. This allows to consider renewable energy technology having different production patterns (for instance wind and solar, or wind production in different zones).

Combined, the above equations (2-5) also ensure that prices can only go above the variable cost of a certain generator, if this generator is already producing at its maximum ($y\_g_{l,s,n}$, $y\_gR_{l,r,n}$ > 0). It is in these periods that the generator accumulates scarcity rents to recover the investment costs, as will be discussed below.

2.1.3 Market operator

As mentioned in the previous section, we assume that there is a market operator that tries to clear both nodes at the same prices, but prices can diverge in case of the congestion on the border. For the elemental electricity system that we consider in this paper consisting of two zones/nodes interconnected by one power line with capacity $Tcap$, the following equations are added:

Equation (6): $\sum_{s,n} x_{l,s,n} + \sum_{r,n} xR_{l,r,n} + \sum_n z_{l,n} - \sum_n d_{l,n} > 0 \perp y\_bneg_l > 0 \quad \forall l$

Equation (7): $-\sum_{s,n} x_{l,s,n} - \sum_{r,n} xR_{l,r,n} - \sum_n z_{l,n} + \sum_n d_{l,n} > 0 \perp y\_bpos_l > 0 \quad \forall l$

Equations 6 and 7 ensure that in each period, demand is either matched with production, or registered as unsatisfied demand.

Equation (8): $-\sum_{n,s} x_{l,s,n} - \sum_{n,r} xR_{l,r,n} - \sum_n z_{l,n} + \sum_n d_{l,n} + Tcap > 0 \perp y\_fpos_l > 0 \quad \forall\, l \; and \; n = 2$

Equation (9): $\sum_{n,s} x_{l,s,n} + \sum_{n,r} xR_{l,r,n} + \sum_n z_{l,n} - \sum_n d_{l,n} + Tcap > 0 \perp y\_fneg_l > 0 \quad \forall\, l \; and \; n = 2$

Equations 8 and 9 ensure that in each period what is exchanged between the two zones is feasible, given the limited capacity available on the border.

Equation (10): $ElecPrice_{l,n} = y\_bneg_l - y\_bpos_l - (n-1)\left(y_{fpos_l} - y_{fneg_l}\right) \forall\, l, n$

Equation 10 sets the price, based on the dual prices of equations 6 to 9. Note that the dual variables of equation 6 and 7 are the same for the two zones, so if the dual variables of equation 8 and 9 are positive (i.e., the power line is congested) the prices of the zones diverge.

2.2 Generation investment

The second step of the model corresponds to the investment decision of the generators. In this step, generators decide the generation capacities that will be available in the third step. In what follows, we explain how this investment decision has been modeled, first for conventional generation and then for renewable generation.

2.2.1 Conventional technologies

The annual investment capacity cost of conventional technology s at zone n is $CC_{s,n}$ (in €/MW.year). We assume a perfectly competitive electricity market where generators do not invest strategically to increase prices. Instead, generators invest up to the point where the scarcity rents match the investment cost of the technology. The investment decision can then be expressed by the following equation:

Equation (11): $CC_{s,n} - \sum_l y\_g_{l,s,n} t_l > 0 \perp g_{s,n} > 0 \quad \forall\, s, n$

Equation 11 ensures that a conventional technology is only chosen by the model ($g_{s,n} > 0$), if the scarcity rent that this technology will accumulate in a year of production is high enough to recuperate the annual investment capacity cost of this technology type.

2.2.2 Renewable energy technologies

The annual investment capacity cost of renewable energy technology r at zone n is $CCR_{s,n}$ (in €/MW.year). In our model, renewable energy technologies are not yet competitive, i.e. their investment cost is too high to be recuperated with scarcity rents. The investment decision for this type of technology is therefore modified so that there is an additional source of income and investment can occur, which is the role of renewable energy policy:

Equation (12): $CCR_{r,n} - \sum_l y\_gR_{l,r,n}\ aR_{l,r,n}\, t_l - \sum_l RenPremium_n\, t_l > 0 \ \perp \ gR_{r,n} > 0 \quad \forall\, r, n$

Equation 12 ensures that a renewable energy technology is chosen by the model ($gR_{r,n}$ > 0), if the premium (in combination with the scarcity rents) is high enough for the investor to recuperate the investment cost of this technology type. The premium in turn depends on the renewable energy policy, and we model two policy extremes: i) no cooperation and ii) cooperation.

In the no cooperation case, the following equations are added to the model:

Equation (13): $\sum_{l,r} xR_{l,r,n}\, t_l - RNtarget_n > 0 \ \perp \ y\_RNtarget_n > 0 \quad \forall\, n$

Equation (14): $RenPremium_n = y\_RNtarget_n \ \ \forall\, n$

Equation 13 ensures for each zone that the production coming from renewable energy technologies matches the target of that zone. Equation 14 sets the zonal premium equal to the dual price of the equation that forces the model to reach the zonal renewable energy target. In other words, the premium is equalized to the cost of achieving the target, and as a result the model achieves the target.

In the cooperation case, the following equations are added to the model:

Equation (15): $\sum_{l,n,r} xR_{l,r,n}\, t_l - RGtarget > 0 \ \perp \ y_{RGtarget} > 0$

Equation (16): $RenPremium_n = y\_RGtarget$

Equation 15 ensures that the total production coming from renewable energy technologies matches the combined target of the two zones. Note that this means that a zonal target can be achieved with investment in another zone. Equation 16 sets the zonal premium equal to the dual price of the equation that forces the model to reach the renewable energy target. In other words, the premium is equalized to the cost of achieving the target, and as a result the model achieves the target.

2.3 Transmission investment

The first step of the modeling corresponds to the investment decisions of the transmission companies. In this step, transmission companies decide the transmission capacity $Tcap$ that interconnects the two zones in our model. The model decides this variable by enumerating the possible transmission capacities (using a given step size) and selecting the optimal capacity. In the numerical example in the next sections, 40 iterations are implemented with transmission capacity increments of 250 MW per iteration. What is optimal then depends on the transmission policy, and we model two policy extremes: i) no cooperation and ii) perfect cooperation.

In the cooperation case, there is one transmission company that wants to maximize the total welfare, and this is then also the outcome of the model. In the no cooperation case, there are two transmission companies that each want to maximize the welfare in their zone. We assume that they each decide what is optimal for them, without taking into account the impact of their transmission policy in the neighboring zone, and without behaving strategically, and then take the minimum of these two values as the outcome of the model under the no cooperation case.[2] Welfare in each zone is computed as the sum of consumer and producer surplus and congestion revenue minus RES premium and transmission costs. Congestion revenue and transmission costs are equally shared by both zones. The RES premium is shared following RES target responsibility.

3. Numerical example

In this section, we demonstrate how the model behaves with a numerical example. We first introduce the simulation cases and then discuss the results.

3.1 Simulation cases

In what follows, we first introduce the two zone electricity system that the simulation cases have in common, and then describe how the cases have different renewable energy sources and targets.

3.1.1 Two zone electricity system

We focus on a setting with two zones that are interconnected by a single transmission line. Figure 2 illustrates this two-zone electricity system. The two zones have the same consumption profile, and equal access to electricity generation technologies with the same investment costs.

The consumption profile is based on Joskow (2009), where the following load duration curve is used: d_l=22,000 MW – 1.37 H (H being the number of hours between 0 and 8760). We implemented this load duration curve with 10 different time segments of equal size (i.e., 876 hours each). VOLL is fixed to 4000 €/MWh.

The generation capacity cost values is based on Joskow (2010) who considers two conventional generation technologies, i.e. base-load and peak-load plants. In our example, base-load and peak-load plants have an annualized (installed) capacity cost of 300,000 and 80,000 €/MW.year, and a variable cost of 20 and 80 €/MWh, respectively. Renewable generation has an annualized (installed) capacity cost of 150,000 €/MW.year and a variable cost of 1 €/MWh. Following Realizedgrid (2010), the annualized cost of transmission capacity is set to 7000 €/MW.year.

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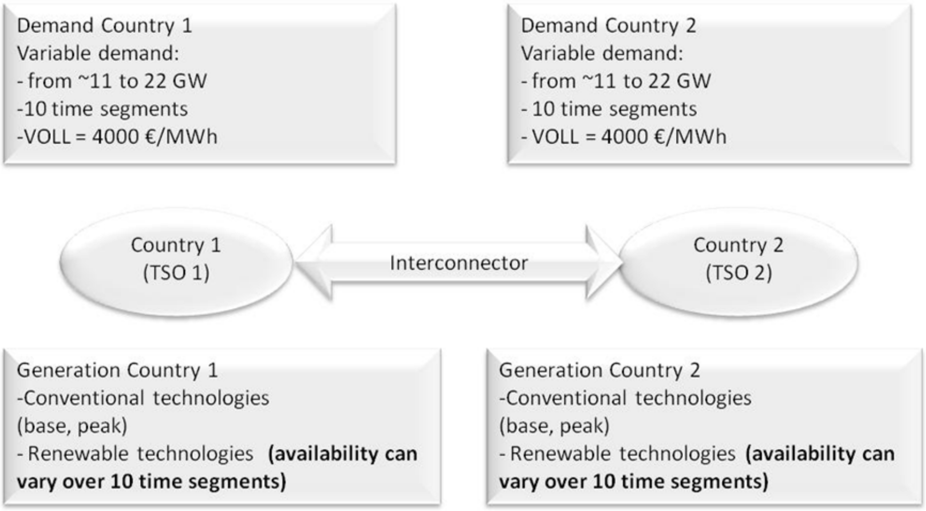
[2] Note that this corresponds to a Nash equilibrium between TSOs playing the following game. The interconnector is composed by two parts: the TSO 1 side and the TSO 2 side. Each TSO invests (can decide capacity) on its own part of the interconnector. As both interconnectors parts are organized in a serial manner, the interconnection capacity between the two zones will be defined by the minimum of the decided capacities. The point used to describe our non-cooperative case is a Nash equilibrium because the TSOs do not have an incentive to deviate from this position.

Figure 2: two-zone electricity system

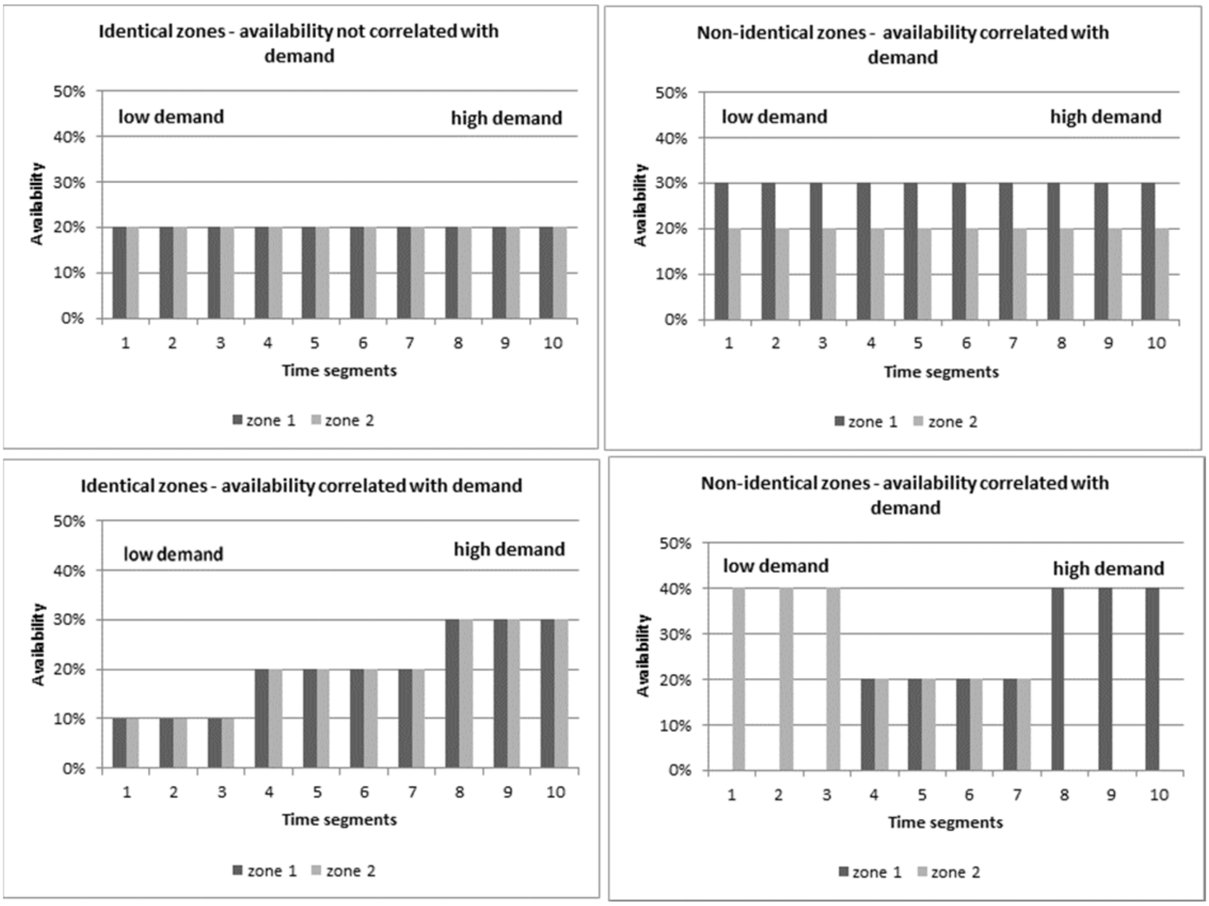


3.1.2 Renewable energy sources and targets

Renewable energy targets are expressed as the percentage of consumption that has to be covered by renewable energy, and we consider targets of 30%, 40% and 50%. Note also that the cost of achieving a renewable energy target is calculated as the welfare result of the model with the target, corrected for the welfare result of the model without the target.

As illustrated in Figure 3, we will look at two simulation cases with identical renewable energy sources in the two zones, i.e. one where the source is positively correlated with demand, another case where this is not. We also look at two simulation cases with non-identical renewable energy sources, i.e. also here one where the source is correlated with demand (positively correlated in one zone, negatively correlated in the other), and one where there is no correlation with demand.

Figure 3: Simulation cases


Identical zones - availability not correlated with demand

Non-identical zones - availability correlated with demand

Identical zones - availability correlated with demand

Non-identical zones - availability correlated with demand

3.2 Simulation results

In what follows, we discuss the simulation results. We first given an overview, and then analyze one of the results in more detail.

3.2.1 Overview

Table 2 illustrates the cost of achieving a 30, 40 or 50% renewable energy target in the different simulation cases under non-cooperative behavior. There are two key observations that can be made based on this table.

First observation is that the cost of achieving a renewable energy target increases with the ambition of the target (30%->40%->50%). The reason is that the targets force the model to invest in renewable technologies, which are non-competitive in the example.

Second observation is that the cost of achieving the renewable energy targets is lowest in the simulation case where one of the zones has a higher availability (non-identical zones – not correlated with demand); next is the case where both zones have an availability that is positively correlated with demand (identical zones – correlated with demand); then the case follows where both zones have the same flat availability (identical zones – not correlated with demand); finally, the highest cost case is one where one of the zones has an availability that is negatively correlated with demand (non-identical zones – correlated with demand).

Table 2: cost of achieving the renewable energy target in the different renewable energy cases under non-cooperative behavior (M€)

		Renewable energy availability	
		Not correlated with demand	Correlated with demand
Zones	Identical	30%: 2824 40%: 3766 50%: 4707	30%: 1648 40%: 2279 50%: 3111
	Non-identical	30%: 1579 40%: 2106 50%: 2632	30%: 2966 40%: 3978 50%: 5081

Cooperative behavior between identical zones has no value. Therefore, we focus on non-identical simulation cases in the rest of the paper. Table 3 illustrates how the costs of achieving a renewable energy target in the different simulation cases decreases with cooperation. There are two key observations that can be made based on this table.

First observation is that renewable energy cooperation always reduces the cost of achieving a renewable energy target. Transmission cooperation however only reduces the cost of achieving the target in cases with ambitious renewable energy targets or in cases with renewable energy sources that are negatively correlated.

Second observation is that the results seem to suggest that it pays more to cooperate in renewable energy development across borders than to cooperation in cross-border transmission capacity investment, but this should not be generalized. Indeed, the relative importance of cooperation in transmission is underestimated in our numerical example because in actual cases, zones differ in many more dimensions than the ones we focused on in our simulation. The existing generation park that can for instance be different, while in our example both zones build a generation park from scratch. Another important difference is that zones typically have different conventional generation investment options, for instance, due to the acceptability of nuclear or access to natural gas.

Third observation is that full cooperation always reduces the cost of achieving a renewable energy target more than cooperation only in transmission or only in renewable energy development across borders. In other words, there are strong interactions between these two forms of cooperation.

Table 3: decrease in the costs of achieving a renewable energy target with cooperative behavior for non-identical zones

Renewable energy availability	Renewable energy target	Cooperative behaviour in transmission	Cooperative behaviour in renewable energy	Full cooperation
Not correlated with demand	30%	0%	37%	41%
	40%	0%	24%	39%
	50%	1%	24%	34%
Correlated with demand (positive in zone 1; negative in zone 2)	30%	4%	40%	57%
	40%	5%	32%	44%
	50%	7%	27%	38%

3.2.2 Details

In what follows, we illustrate the details of what happens in the simulation case with renewable energy sources that have a different availability in the two zones, and are negatively correlated. We focus on the results for a renewable energy target of 40% without cooperation in renewable energy development. Figure 4 illustrates the evolution of total and zonal welfare for increasing investment in transmission capacity between the two zones. There are three key observations that can be made based on this figure.

First observation is that total welfare increases steeply until the transmission capacity reaches 3750 MW, after which it slowly decreases. The slow decrease is caused by the cost of transmission. The increase is mainly due to an increase of welfare in zone 1, and a smaller increase of welfare in zone 2.

Second observation is that welfare in zone 2 is significantly lower than the welfare in zone 1 because the renewable energy source of zone 2 is negatively correlated with demand, while the renewable energy source of zone 1 is positively correlated with demand in the simulation case we have selected for detailed discussion.

Third observation is that zonal welfare in both zones increases for increasing investment in transmission until the cross-border capacity reaches 2250 MW, after which the zonal welfare of zone 2 starts to decrease. In other words, in the non-cooperative policy case transmission will be 2250 MW and cooperation will increase this capacity to 3750 MW.

Figure 4: Evolution of welfare for increasing transmission capacity

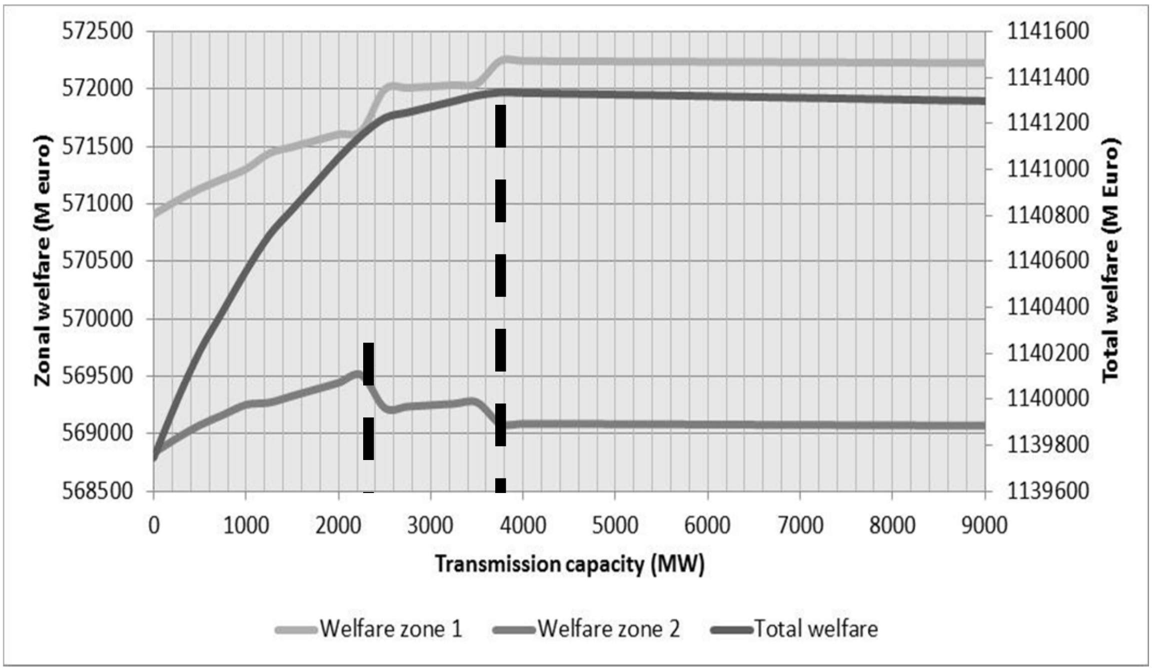


Figure 5 illustrates the evolution of installed generation capacities for increasing investment in transmission capacity between the two zones with steps of 750 MW up to 4500 MW.[3] There are two key observations that can be made based on this figure.

First observation is that total capacity reduces with about 8 GW, i.e. from around 105 GW with no transmission capacity to 97 GW with 3750 MW of transmission capacity. The reduction in installed generation capacity mainly takes place in zone 2 that has the less favorable renewable energy source. Indeed, in zone 2 renewable energy capacity reduces with more than 3 GW, conventional peak capacity reduces with almost 3 GW, while conventional base capacity increases with just over 1 GW.

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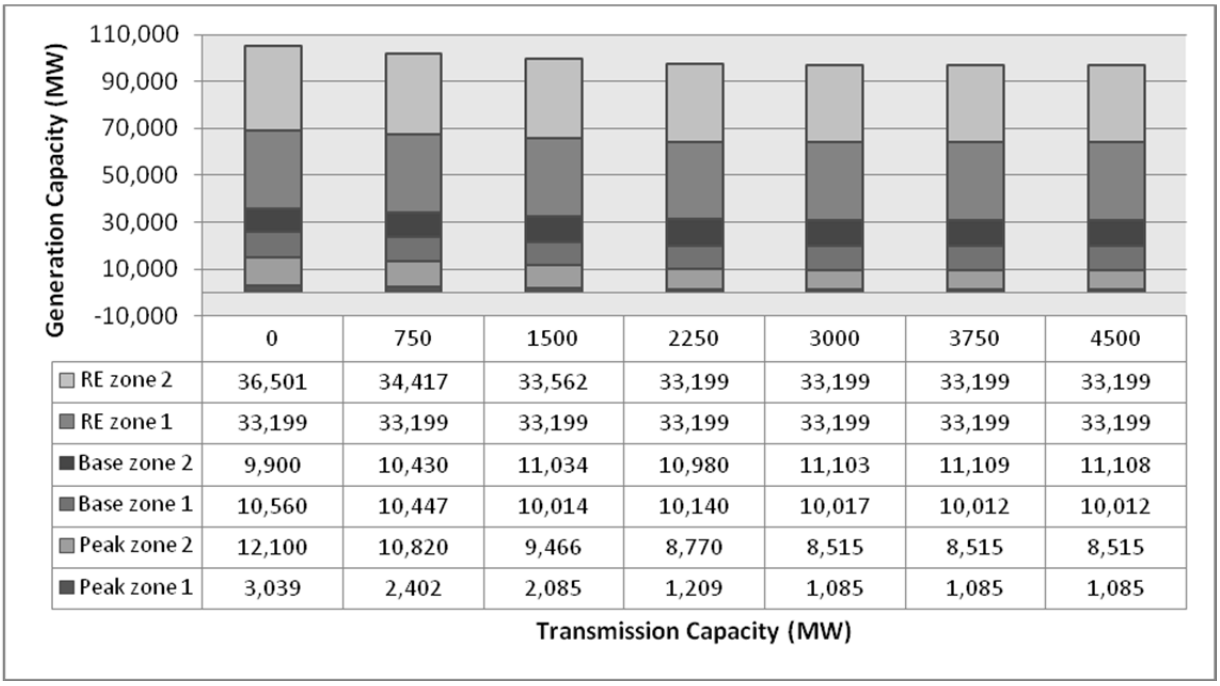
[3] Note that the model calculates with steps of 250 MW. We illustrate less steps to increase the readability of the figure, and choose 750 MW so that 2250 and 3750 MW are included, which are the capacities corresponding to the investment in the non-cooperative and cooperative transmission policy case, respectively.

In zone 1, on the contrary, renewable energy capacity remains unchanged, conventional peak capacity reduces with almost 2 GW and conventional base capacity reduces with less than half a GW.

Second observation is that less renewable energy capacity is needed to achieve the same volume of renewable energy, as the cross-border transmission capacity between the zones increases. Zone 2 indeed has a renewable energy source that is negatively correlated with demand so that renewable energy is spilled in hours with low demand. The increase in cross-border transmission capacity implies that zone 2 can export its renewable energy to zone 1 in hours of low demand so that less renewable energy is spilled. Note that for zone 1 it implies that less conventional generation capacity is needed.

Figure 5: Evolution of the installed generation capacity mix for increasing transmission capacity



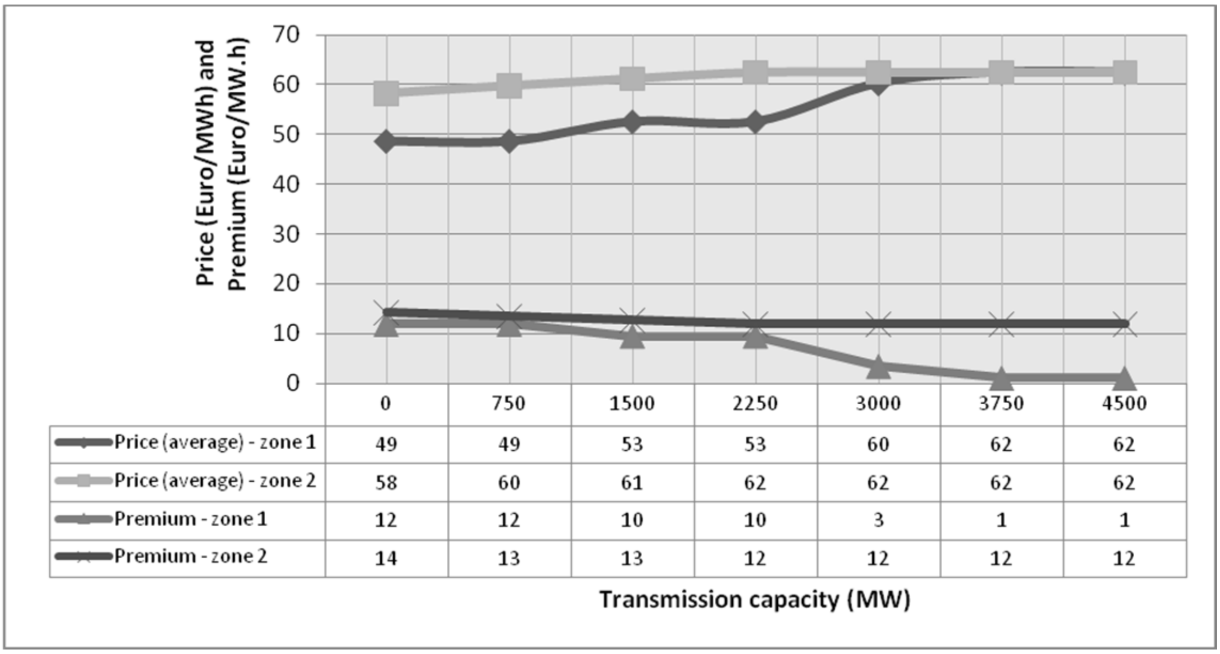
	0	750	1500	2250	3000	3750	4500
RE zone 2	36,501	34,417	33,562	33,199	33,199	33,199	33,199
RE zone 1	33,199	33,199	33,199	33,199	33,199	33,199	33,199
Base zone 2	9,900	10,430	11,034	10,980	11,103	11,109	11,108
Base zone 1	10,560	10,447	10,014	10,140	10,017	10,012	10,012
Peak zone 2	12,100	10,820	9,466	8,770	8,515	8,515	8,515
Peak zone 1	3,039	2,402	2,085	1,209	1,085	1,085	1,085

Figure 6 illustrates the evolution of prices for increasing investment in transmission capacity between the two zones with steps of 750 MW up to 4500 MW. The electricity price is a weighted average, i.e. the electricity prices of the ten time segments considered in the model weighted with the consumption in the time segment. Remember that we model perfect competition so that producers invest until short-run profits are just enough to cover fixed (capacity) costs. As a result, an electricity price increase implies a reduction in zonal welfare because it reduces consumer surplus, while producer surplus is zero. An increase in renewable energy premium also reduces consumer surplus, while producer surplus for renewable energy technologies are also zero in the model so that this also reduces the zonal welfare. Note also that the impact of electricity prices on welfare is relatively stronger because it is proportional to consumption, while the impact of the renewable energy premium on welfare is proportional to the installed renewable energy capacity.

First observation is that in zone 1, the evolution of prices is different from 0 to 2250 MW than from 2250 to 3750 MW cross-border transmission capacity. From 0 to 2250 MW, there is a slight increase in electricity prices, a slight decrease in the renewable energy premium in zone 1, and based on Figure 4 we know the net effect on zonal welfare is positive. From 2250 MW to 3750 MW, there is a sharper increase in electricity prices, and also a sharper decrease in the renewable energy premium in zone 2, and based on Figure 4 we know that the net effect on zonal welfare is negative.

Second observation is that in zone 2, prices steadily increases, but the renewable energy premium decreases, and based on Figure 4 we know that the net effect on zonal welfare is positive from 0 to 3750 MW cross-border transmission capacity.

Figure 6: Evolution of prices for increasing transmission capacity



	0	750	1500	2250	3000	3750	4500
Price (average) - zone 1	49	49	53	53	60	62	62
Price (average) - zone 2	58	60	61	62	62	62	62
Premium - zone 1	12	12	10	10	3	1	1
Premium - zone 2	14	13	13	12	12	12	12

Conclusions

In this paper, we analyzed how cooperative behavior in developing renewable energy technologies across borders and/or developing cross-border transmission capacity can reduce the cost of achieving a renewable energy target. We developed a three step model with: i) transmission investment, ii) generation investment and iii) electricity market that we applied to a numerical example of an interconnected two zone system.

Our analysis showed that, in the two zone system described, the cost reduction that can be achieved depends on the differences between zones, and the ambition of the renewable energy target. We explored how differences in the availability and correlation of renewable energy sources in the two zones impact the results, and how these results interact with the ambition of the renewable energy target that the zones want to achieve.

We find that both types of cooperation can result in a significant reduction of the cost to achieve the renewable energy targets, and there are also strong interactions because cooperative behavior in developing renewable energy technologies across borders and cross-border transmission capacity investment always outperforms cooperation that is restricted to renewable energy or transmission. We also showed that it is the zone that has the less favorable renewable energy sources that will invest less in cross-border transmission capacity in policy cases with non-cooperative transmission development.

The policy implication of our analysis is that the cost savings that can result from two countries cooperating in the development of renewable energy technologies will depend on how different their renewable energy sources are, and on their willingness to cooperate in transmission developments across their borders. This is therefore an important interaction to take into account in renewable energy policy discussions.

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Appendix 1: Nomenclature

Sets

s	Types of plant - conventional technologies (e.g., coal, gas, etc)
r	Types of plant - renewable technologies (e.g., wind, PV, etc)
l	Time segment of load duration curve
n	zones (e.g., France, Germany)

Parameters

Type	Name	Description	Unit
Demand	$VOLL$	Value of lost load	
	$d_{l,n}$	demand in time segment l at zone n	MW
	t_l	duration of time segment l (the sum of t(l) is equal to 8760)	Hours
Generation	$CC_{s,n}$	annual investment capacity cost for conventional technologies	[€\MW.year]
	$VC_{s,n}$	variable cost for conventional technologies	[€\MWh]
	$CCR_{r,n}$	annual investment capacity cost for renewables	[€\MW.year]
	$VCR_{r,n}$	variable cost for renewable	[€\MWh]
	$aR_{r,l,n}$	Availability factor for renewable r at zone n and for time segment l	
Transmission	CCT	annual capacity cost transmission	(€/MW.year)
	$Tcap$	transmission capacity of interconnector	MW
Renewable policy	$NRenTarget_n$	minimal annual renewable energy to be produced at zone n	MWh.year
	$GRenTarget$	minimal annual renewable energy to be produced in both zones	MWh.year

Variables

Type	Name	Description	Unit
(Primal) Variables	$x_{l,s,n}$	generation of conventional plant type s at the segment period l and zone n	MWh
	$g_{s,n}$	maximal generation output (capacity) of conventional plant type s at zone n	MW
	$xR_{l,s,n}$	generation of renewable plant type r at the segment period l and zone n	MWh
	$gR_{r,n}$	maximal generation output (capacity) of renewable plant type r at zone n	MW
	$z_{l,n}$	unsatisfied demand in time segment l at zone n	MW
(Dual) variables	$y\_g_{l,s,n}$	dual variable for maximal production constraint for each plant s at time segment l and zone n (this variable is > 0 when constraint of conventional capacity is active)	€/MWh
	$y\_gR_{l,r,n}$	dual variable for maximal production constraint for each plant r at time segment l and zone n (this variable is > 0 when constraint of renewable capacity is active)	€/MWh
	y_bpos_l	dual variable for positive balance constraint (this variable is > 0 when balance constraint is active in one direction)	€/MWh
	y_bneg_l	dual variable for negative balance constraint (this variable is > 0 when balance constraint is active in the other direction)	€/MWh
	y_fpos_l	dual variable for positive flow constraint of interconnector (this variable is > 0 when there is congestion in line l in one direction)	€/MWh
	y_fneg_l	dual variable for negative flow constraint of interconnector (this variable is > 0 when there is congestion in interconnector in the other direction)	€/MWh
	$y\_RGtarget$	dual variable for renewable energy global constraint or renewable energy premium (this variable is > 0 when there is not enough renewable generation, i.e., renewable energy premium has a positive price)	€/MW.h
	$y\_RNtarget_n$	dual variable for renewable energy constraint on zone n or renewable energy premium in zone n (this variable is > 0 when there is not enough renewable generation at zone n, i.e., renewable energy premium at zone n has a positive price)	€/MW.h
(Output) variables	$ElectPrice_{l,n}$	Electricity price	€/MWh
	$RenPremium_n$	Renewable energy premium	€/MW.h
	CS_n	National consumer surplus	€/year
	PS_n	National generator surplus	€/year
	CR_n	National congestion revenue	€/year
	GW	Global Welfare	€/year
	NW_n	National Welfare	€/year

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