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Vertical Disintegration in the European Electricity Sector: Empirical Evidence on Lost Synergies

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Abstract: *The EU has been promoting unbundling of the transmission grid from other stages of the electricity supply chain with the aim of fostering competition in the upstream stage of electricity generation. At presence, ownership unbundling is the predominant form of unbundling in Europe. However, the benefits of increased competition from ownership unbundling of the transmission grid may come at the cost of lost vertical synergies between the formerly integrated stages of electricity supply. The policy debate generally neglects such potential costs of unbundling, yet concentrates on its benefits. Therefore European cross-country evidence may shed some light on this issue. This study helps fill this void by empirically estimating the magnitude of economies of vertical integration (EVI) between electricity generation and transmission based on a quadratic cost function. For this purpose we employ novel firm-level panel data of major European electricity utilities. Our results confirm the presence of substantial EVI, which put the policy measure of transmission ownership unbundling into question.*

Keywords: Cost function, Economies of Scope, Ownership Unbundling, Vertical Integration

JEL codes: L22, L25, L51, Q48

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1. Introduction

Before the introduction of liberalization and regulatory reforms, in order to promote competition in the European electricity sector, electricity utilities were generally regarded as natural monopolies. Electricity is a particularly special good which includes some important characteristics: (i) On a large scale, electricity cannot be easily stored, which requires supply to meet demand at all times. Therefore, suppliers need to have sufficient excess capacities to meet peak demand. (ii) Electricity follows physical laws (Ohm's and Kirchoff's laws) and flows its way of least resistance. (iii) Generated electricity has to be transported to customers via long-distance high-voltage transmission lines and locally via lower-voltage distribution lines. (Arocena et al., 2012; Ramos-Real, 2005) Under these conditions, the supply of electricity is highly interlinked along the various supply stages and, henceforth, subject to coordination requirements (Gugler et al., 2013).

In the classical fashion, vertical integration of upstream and downstream operations was the predominant organizational form of an electricity utility to benefit from scope economies of vertical integration. A fully vertically integrated electricity company would encompass all stages from electricity generation, over high-voltage transmission of electricity, to local distribution, in conjunction with system operations, retailing to final consumers, and wholesale power procurement (e.g. Hunt, 2002). It seems natural that vertical integration exhibits cost savings through coordination advantages, sharing of information, use of common inputs, sharing of staff, efficient planning of investments, protection against uncertainty and financial risk, among other factors, which cannot be easily realized by unbundled firms (Jara-Díaz et al., 2004; Meyer, 2012). Henceforth, vertical integration seems to be a more efficient organizational form compared to leaving the coordination of the vertical supply to the market. (Arocena et al., 2012)

In recent decades, the unbundling principle (i.e. vertical separation) has been put into practice in many economies around the globe. This regulatory measure has the aim to isolate some segments of the electricity supply chain, which do not exhibit the usual properties of a natural monopoly (e.g. generation, retails), for the sake of eliminating anti-competitive forces and lowering the electricity price for end-consumers through increased competition (Fraquelli et al., 2005). The remaining segments – the transmission grid and the distribution lines – feature typical network characteristics associated with a natural monopoly and, thus, need to be regulated.[1]

However, a controversial debate has arisen whether the benefits of increased competition may be offset by potentially increased costs of utilities from unbundling.[2] The policy discussion has put little attention to the fact that the regulatory measure of vertical disintegration comes at a cost, namely the destruction of vertical economies. According to Meyer (2012a) the greatest vertical synergies occur between *generation* and *transmission*, for which the largest cost savings are to be expected. Against this background, it is relevant to assess if and how large these vertical economies may be. Most of all, it is important to consider these potential costs of unbundling in the policy debate.

Indeed, the European Union has already put vertical disintegration of the high-voltage *transmission* grid into practice (starting with to the EU directive 1996/92/EC; Schmitt and Kucera, 2013).[3] Therefore, vertical structures of electricity utilities have been broken up, and simultaneously, third party access to the transmission grid has been granted for entrants. The most recent EU directive 2009/72/EC requires its Member States to choose from three different forms of vertical unbundling of the transmission grid: (i) full ownership unbundling (the predominant form in Europe), (ii) the implementation of an independent system operator (ISO), or (iii) the implementation of an independent transmission operator (ITO).[4] Among them, ownership unbundling represents the most restrictive type, where vertically integrated electricity utilities have to fully separate from their transmission grid. Hence, with ownership unbundling it is possible to detect the new transmission operator as an own firm in the data, while the previously integrated firm loses its transmission network.

While the empirical literature in general finds considerable cost savings from vertical economies for US electricity utilities, limited empirical literature on single-country studies points toward modest cost savings in Europe. In brief, empirical evidence questions the effectiveness of the divestiture of integrated utilities in the electricity industry, whereby evidence from Europe is scarce and not as distinctive as from the US. Noticeably, not only the regulatory framework but also the structure of the electricity industry differ between the US and Europe in many respects, which makes a direct comparison difficult (Meyer, 2012a).

[1] For example, by introducing price regulation (grid tariffs) and third party access.
[2] Sappington (2008) discusses the benefits of vertical divestiture to maximize consumer welfare despite the presence of substantial vertical economies. Gugler et al. (2013) show that there is a trade-off between static and dynamic efficiency in this context.
[3] Contrary, the level of unbundling of *distribution* lines lags far behind.
[4] Balmert and Brunekreeft (2010) provide a description of the various forms of transmission unbundling.

Moreover, the predominant share of the literature concentrates on the estimation of scope economies between the stages of generation and *distribution*, for which data seem to be easier available. Contrary, there is hardly evidence on cost savings from integration between generation and *transmission*. Since the EU law explicitly requires unbundling of the transmission grid, such information would be of utmost relevance and promotes one decisive feature of this study.

We, therefore, concentrate on the efficiency and effectiveness of vertical divestiture of the supply stages of *generation* and *transmission* of European electricity utilities. To achieve this goal, we quantify vertical scope economies based on the estimation of a multistage quadratic cost function. If vertical economies were found to be large, it would indicate that the regulatory measure of ownership unbundling of the transmission grid may come at substantial costs.

We utilize novel firm-level data on 28 major European electricity utilities from 16 European countries for the annual date for the period 2000–2010. Data are collected from annual reports and combined with data sources from Platts, Orbis, Worldscope, and OECD. To the best of our knowledge, the paper is the first to provide empirical cross-country evidence for Europe regarding economies of scope from vertical integration in the electricity sector. A key benefit of this study is its focus on generation versus *transmission*, while most of the remainder literature has concentrated on generation versus distribution. The data allow for exploiting vertical economies through mixed company structures, since the sample represents all organizational forms of generators, transmitters, and vertically integrated utilities.

Against this background, this analysis tries to shed some light on the consequences of transmission unbundling as a regulatory means. This is of particular interest not only for regulatory authorities and policy-makers, which are concerned with the optimal form of regulation, but also for end-consumers who eventually have to finance the electricity system via electricity taxes and (higher) prices.

The paper is organized as follows. Section 2 provides a summary of the relevant literature about scope economies in the electricity sector. Section 3 describes the theory on scope economies and their potential sources. The model specification and estimation strategy are presented in Section 4. Section 5 discusses the underlying data for the econometric analysis. The results are provided in Section 6, where we present not only regression results and robustness checks but also the quantification of scope economies for different firm dimensions. Section 7 concludes the findings and derives policy implications.

2. Review of relevant empirical literature on vertical economies in electricity

The main body of the empirical literature on vertical economies in the electricity sector investigates the stages of generation and the network, where the latter is either represented by the distribution network or a combination of the distribution and the transmission network. Some early works have concentrated on the separability and sub-additivity of the vertical supply stages in the electricity sector (e.g. Gilsdorf, 1994; Hayashi et al. 1997; Lee, 1995; Roberts, 1986; Thompson, 1997). The findings generally indicate non-separability of the cost function,[5] which point toward the presence of vertical scope economies. Subsequently, empirical studies have started to directly implement the concept of multi-output theory with the primary appeal to estimate the *magnitude* of vertical synergies in the electricity markets. Both, Arocena et al. (2010) and Ramos-Real (2005) provide thorough literature reviews. In the following, we discuss the relevant literature on vertical cost synergies at the US and European electricity sectors. Thereby we put emphasis on the stages of generation and distribution, as well as generation and transmission, respectively.

A great deal of the empirical nexus on scope economies from vertical integration between generation and *distribution* focuses on the US. A seminal contribution has been the article by Kaserman and Mayo (1991), who apply a quadratic cost function and estimate 12 percent cost savings at the sample mean for 74 US electricity companies in 1981. Hayashi et al. (1997) focus on 50 US utilities with at least 85 percent of generation from fossil fuels for the period 1983–1987 and apply a translog cost function. The results show vertical economies of around 17 percent for the average utility (a sample split into small and large utilities shows evidence of vertical economies of 14 percent and 17 percent, respectively). Kwoka (2002) examines data on 147 US utilities for the year 1989 and finds substantial vertical economies based on a quadratic cost function. While for very small utilities stand alone production is a viable strategy, larger companies do profit from cost savings from vertical integration. At the median and mean level, scope economies are calculated at 27 and 42 percent respectively. Greer (2008) utilizes a sample of 831 US rural utilities in 1997. Estimates from a modified quadratic cost function reveal cost savings from vertical integration for basically all utilities. Similar to

[5] Non-separabilitiy of the cost function means that downstream activities of transmission and distribution are dependent on upstream generation.

Kwoka's (2002) findings, economies of scope for the average utility are in the order of 40 percent.

Triebs et al. (2012) apply a flexible approach of the cost function by allowing for differences in technologies across integrated and specialized firms. Their results from an unbalanced panel of US utilities for the period 2000–2003 indicate moderate scope economies of 4.4 percent, putting previous findings into perspective. Arocena et al. (2012) incorporate data on 116 US investor owned utilities for the year 2001 and estimate a quadratic cost function. Vertical economies are estimated in the scope of eight percent, while horizontal economies (across different types of generation) make up around 5.5 percent for the average utility.

In contradiction of the pronounced empirical literature on the US electricity industry, the European literature on multi-output cost-function estimation of vertical scope economies is relatively limited. To the best of our knowledge, merely single country studies but no cross-country analysis exists. The Spanish electricity market has been investigated by Jara-Díaz et al. (2004), who employ an unbalanced panel of 12 Spanish electricity utilities for 1985–1996. The average firm in their sample exhibits vertical economies of 6.5 percent and horizontal economies of around ten percent. With regard to Italy, Fraquelli et al. (2005) make use of a composite cost function on 25 municipal electric utilities for the period 1994–2000 and estimate vertical cost savings of 3 percent. The same dataset is used by Piacenza and Vannoni (2004)[6] who compare estimates from different cost function specifications (generalized translog, standard translog, separable quadratic, composite, and general[7]). Their preferred model, the composite form, yields vertical economies in the magnitude of 6 percent for the median utility. Fetz and Filippini (2010) concentrate on the Swiss electricity sector. The estimation of a quadratic cost function of 74 utilities over 1997–2005 yields substantial vertical economies far beyond 40 percent on average.[8] This may be explained by the relatively small size of the sample utilities having generally less than 100,000 customers.

As far as we know, Meyer (2012a) is the only empirical study to investigate scope economies between electricity generation and *transmission*. Based on data from the US for the period 2001–2008, his findings indicate modest vertical synergies between the two stages of approximately four percent for the average firm. This is explained by a *coordination effect* from transaction cost theory: "firm internal coordination is expected to be more efficient than

[6] Contrasting to Fraquelli et al. (2005), Piacenza and Vannoni (2009) employ different output measures, with the purpose to investigate not only vertical but also horizontal economies at the distribution stage.
[7] The composite and general forms are implemented according to Pulley and Braunstein (1992).
[8] The exact magnitude of vertical economies for the mean or median utility is not provided in the paper.

market coordination as a result of costly, incomplete and/or inflexible contracts of market participants pursuing different or opposing interests." (Meyer, 2012a, 105) Yet, Meyer warns against a potential bias of a comparison of his results with findings for Europe because of different market structures and initial unbundling conditions[9]. Besides, his results show the presence of vertical economies between generation and the whole network of transmission plus distribution of 19 to 26 percent and vertical economies between distribution (including retail) and generation plus transmission of eight to ten percent.

Against this review of the empirical literature, vertical economies of scope in the electricity industry appear to exist, whereas contrasting findings regarding the *magnitude* of estimated cost savings from vertical integration may stem from different factors. Among them are: (i) the heterogeneity of utilities (e.g. size, corporate form, geographic region, regulatory framework) included in the data; (ii) the specification of the cost function; (iii) different measures of outputs and inputs; and (iv) diverging periods of observation. Some evidence from US electricity markets corroborates the presence of substantial cost savings from vertical integration. Clearly, vertical synergies in the European electricity sectors are under-researched, foremost because only single countries have been investigated. Overall, the effectiveness of vertical ownership unbundling is being questioned despite its potential positive effects (e.g. increased competition, lower end-consumer prices). Since European cross-country scrutiny is missing, the purpose of this paper is to help fill this void in the literature.

3. Multiproduct theory and sources of vertical economies

The concept of economies of scope roots from the multiproduct production theory, based on the idea that there may be potential cost savings from jointly producing two outputs in contrast to separate production. Transaction theory provides the explanation that "firm internal coordination is expected to be more efficient than market coordination" (Meyer, 2012a, 105). Consequently, the vertically integrated supply of upstream electricity generation and downstream electricity transmission may be cost efficient over a separated production process, as suggested by transmission ownership unbundling. Hence, vertical scope economies exist if the costs of separating the supply stages of generation (Y_G) and transmission (Y_T) exceed their combined production costs:

[9] In the US many states have implemented Regional Transmission Operators (RTO), which basically incorporate the role of European ISO.

$$C(Y_G,0)+C(0,Y_T)-C(Y_G,Y_T)>0. \tag{1}$$

The magnitude of economies of vertical integration (EVI) can be measured as the cost savings of jointly serving both stages relative to the costs of separated supply (Kwoka, 2002):

$$EVI=[C(Y_G,0)+C(0,Y_T)-C(Y_G,Y_T)]/[C(Y_G,0)+C(0,Y_T)]. \tag{2}$$

By exploiting vertical economies of scope, electricity utilities are able to obtain benefits for various reasons. In general, the complexity of the electricity sector and its interdependency among the different supply stages requires a high degree of coordination. In particular, integrated utilities may reduce their costs by coordinating dispatches of utilities' plants according to the actual merit order[10]. Those vertical synergies may be lost with transmission unbundling and, hence, uncoordinated dispatches may shift costs closer to the more expensive reserve power. Besides optimizing economic dispatch of generating plants, Arocena et al. (2012) highlight coordination advantages from efficient plant investment, planning of maintenance schedules, maintenance of spinning reserves[11], and risk management.

Additionally, Baumol et al. (1982) point out that firms may save on costs by sharing common inputs among different stages of operations. It is most likely that electricity utilities may reduce costs by sharing capital and labor among the supply stages generation and transmission. Additionally, coordination advantages may arise due to technological interdependency of the operational stages of electricity supply (Gugler et al., 2013). Immediate coordination is required in so far as demand has to meet supply at all times. For this instance, the operational stages of electricity supply are interdependent and require informational transactions. "Since the strongest interaction occurs between generation and transmission, one would expect the most significant synergies between these stages." (Meyer, 2012a, 97) Other synergies may stem from sharing common production or maintenance tasks, and from the common usage of buildings, administrative staff, or IT software. Another source of vertical synergies may arise from efficient planning of investments by sharing accurate information among the various operational stages. Given these possibilities for attaining

[10] In order to ensure equality of electricity supply when demand is declining, electricity plants may be dispatched from the network according to the merit order, which represents the short-term supply curve of electricity production based on ascending order of power plants' marginal costs.
[11] The spinning reserve is the capacity reserve provided by the generating units actually connected to the power grid. In contrast, generating units not connected to the grid contribute to the non-spinning reserve.

vertical economies of integration, their loss from ownership unbundling of the transmission grid may increase the costs of utilities substantially.[12]

4. Model specification and estimation strategy

This study incorporates the quadratic specification of the cost function, which has been introduced by Baumol et al. (1982) and has been widely applied since for estimating scope economies in electricity markets. It provides several advantages over other specifications. Firstly, the quadratic is regarded as relevant for the estimation of cost savings from vertical integration (Farsi et al., 2008; Farsi and Filippini, 2004). Secondly, compared to the translog cost function, the quadratic readily handles the zero-values problem (Jara-Díaz et al., 2004). In the case of estimating vertical scope economies, this problem becomes particularly severe because, by definition, specialized production of one output requires zero values for the other output(s).[13] Thirdly, given its prevalent application, results obtained from a quadratic cost function allow for a direct comparison with other studies (Meyer, 2012). In contrast, the quadratic cost function represents a second order Taylor approximation of its true unknown form. Hence, its corners may be poorly estimated and should be interpreted with caution.[14]

It is of importance to highlight that many other empirical studies on economies of vertical integration, base their analyses on the estimation of a *reduced form* of the full specification of the cost function and/or do not impose all relevant restrictions (Farsi and Filippini, 2004; Fetz and Filippini, 2010; Kwoka, 2002; Meyer, 2012; Nemoto and Goto, 2004). The large estimates of cost synergies in previous papers (as mentioned in Section 2) may partly arise because "the cost function is not completely specified, as the input cost-share equations are not estimated together with the cost equation, many price interaction terms are excluded, and linear homogeneity restrictions are not imposed" (Arocena et al., 2012, 439).

[12] Notwithstanding the synergy losses associated with vertical divestiture, Meyer (2012b) argues that firms subject to ownership unbundling would restructure their organizational form in order to obtain specialization advantages.
[13] Pulley and Braunstein (1992, 223) mention that "(…) the estimated translog cost function cannot be used to measure the costs of specialized production, as is required to estimate economies of scope or product-specific economies of scale." Even though some studies (e.g. Hayashi et al., 1997) try to overcome this dilemma by replacing zero values by an arbitrarily small value, Triebs et al. (2012) argue that such estimates of scope economies may suffer from significant bias. Other functional forms, for example the composite cost function, allow for zero values in outputs (Fraquelli et al., 2005) but bear disadvantages, such as highly non-linear parameters and no economic meaning of coefficients (Triebs et al., 2012).
[14] We will come back to this issue in Section 6.2, when we interpret the magnitude of EVI at large output combinations (e.g. near the 90^{th} percentiles).

We, therefore, estimate the *full specification* of the cost function, which includes a full set of interaction terms between outputs and input prices:

$$C_{it} = \alpha_0 + \alpha_G + \alpha_T + \sum_j \beta_j Y_{it}^j + 0.5 \sum_j \sum_k \beta_{jk} Y_{it}^j Y_{it}^k + \sum_l \gamma_l w_{it}^l + 0.5 \sum_l \sum_m \gamma_{lm} w_{it}^l w_{it}^m + \sum_j \sum_l \delta_{jl} Y_{it}^j w_{it}^l + \rho' Z_{it} + \varepsilon_{it} \quad (3)$$

The subscripts i and t stand for the utility and year, respectively. The dependent variable (C) represents the total costs, Y includes measures for outputs, w stands for measures for input prices, Z is a set of cost shifting variables, and ε is the error term. The two outputs of generation and transmission are given by $j = \{G, T\}$, the three input prices of labor, capital, and fuel are given by $l = \{L, C, F\}$. The constants for overall operations, generation-specific operations, and transmission-specific operations are represented by α_0, α_G and α_T, respectively.

The constant α_0 represents the joint fixed costs of an integrated utility, which operates at both stages of generation and transmission. These may arise, for example, from the usage of common facilities or common staff. Kwoka (2002, 659) mentions that "α_0 represents the costs of any indivisible input, costs that would be duplicated by separate production (…)." In contrast, α_G and α_T are fixed costs of stand-alone provision of the supply stages of generation and transmission, respectively. Of particular interest is the estimated parameter on the output interaction between generation and transmission, β_{GT}. A negative sign indicates variable cost synergies associated with the joint operation of generation and transmission within one electricity utility relative to separated operations.

Sheppard's Lemma is applied in order to enhance the performance of the regression by estimating the cost function together with its input shares (Christensen and Green, 1976).[15] This imposes no additional parameters but increases the degrees of freedom of the model (Martínez-Budría et al., 2003). The input shares read as follows:

$$\frac{\partial C_{it}}{\partial w_{it}^l} = x_l = \gamma_l + \sum_m \gamma_{lm} w_{it}^m + \sum_j \delta_{jl} Y_{it}^j + \varepsilon_{it}^l \quad (4)$$

where x_l represents the quantity of input l, and ε^l is the corresponding error term.

Moreover, we introduce several restrictions to meet the assumptions of a standard cost function. A well-behaved cost function assumes *linear homogeneity* in input prices, so that an

[15] Note that it is necessary to drop the input share equation regarding the input price which is used for normalization of costs and input prices.

increase in input prices proportionally increases total costs. This condition is imposed by dividing total costs and input prices by an arbitrarily chosen input price.[16] Furthermore, we assume symmetry for the β and γ parameters, so that $\beta_{jk} = \beta_{kj}$ and $\gamma_{lm} = \gamma_{ml}$. Additionally, we assume cost minimization of utilities and that outputs and input prices are determined exogenously. This seems to be a valid assumption under the circumstance that "factor prices are determined in competitive markets or through regulation, while electricity output is determined by consumer demand." (Arocena et al., 2012, 444)

5. Data

This analysis utilizes a novel dataset of European electricity utilities. We focus on major utilities in order to ensure some degree of homogeneity. Foremost, contrary to small operators, large utilities are more likely to incorporate a transmission grid, if vertically integrated. Data are collected from the firms' annual reports and are combined with other sources (Platts, Orbis, Worldscope, OECD). Limitations on data availability of relevant variables eventually led to the utilization of data from 28 major European electricity utilities from 16 European countries for the period 2000–2010.

Table 1. Sample statistics

Description	Variable	Obs.	Mean	Std. Dev.	Min.	Max.
TOTEX excl. purchased power (bnEUR)	C	242	7.36	11.88	0.12	57.90
Generation (TWh)	Y_G	242	74.80	136.85	0.00	669.00
Transmission (tKm)	Y_T	242	9.80	21.65	0.00	100.69
Price of labor (tEUR/empl.)	w_L	242	57.69	21.53	12.07	141.01
Price of natural gas (tEUR/GWh)	w_F	242	26.03	8.55	9.75	44.78
Price of capital (%)	w_C	242	7.05	3.77	0.68	30.32
Hydro Capacity (%)	hyd	242	28.28	26.63	0.00	100.00
Nuclear Capacity (%)	nuc	242	11.77	17.10	0.00	61.46
Binary indicator: generation only	α_G	242	0.43	0.50	0.00	1.00
Binary indicator: transmission only	α_T	242	0.12	0.33	0.00	1.00

Notes: Obs. is observations, Std. Dev. is standard deviation, Min. is minimum, Max. is maximum, tEUR is thousand EUR, bn EUR is billion (10^9) EUR, tKM is thousand Km, TWh is thousand GWh.

[16] In our case we divide costs and input prices by the price of fuel.

The utilities in our sample cover 74 percent in total load of their respective countries.[17] Some missing values in the data emanate from a lack of information in the respective annual reports or from other data sources.[18] Hence, the sample is structured as an unbalanced panel. When possible and reasonable, single missing observations were inter- or extrapolated. In total, the sample comprises 242 observations. Summary statistics for all variables employed in this analysis are provided in Table 1. The sample includes all organizational company structures of pure generators, pure transmission operators, and vertically integrated utilities. Appendix Table A1 provides an overview of the electricity utilities covered by the sample.

5.1.Dependent variable

The dependent variable, total costs, represents the sum of capital and operating expenditures. One particular concern on the estimation of multistage cost functions is to avoid any potential double-counting of expenses for purchased electricity (e.g. Kwoka, 2002; Jara-Díaz et al., 2004; Meyer, 2012). Consequently, expenditures for purchased electricity have to be excluded from the total costs of utilities, which obtain all or a part of their electricity from external sources. Kaserman and Mayo (1991) have neglected to subtract purchased powers from total costs in their seminal paper, and have consequently been largely criticized by successive works.[19] Unfortunately, data on *expenses* on purchased power were largely not available. For that reason, we collected data on the *amount* of purchased power from annual reports of the utilities in our sample. The amount of purchased power was then multiplied by the spot market price of electricity, obtained from the European Energy Exchange for the respective years. This made it possible to exclude purchased power from total costs.[20]

[17] The comparison is based on OECD data on total national load for the available period 2003–2010: 2003: 69%, 2004: 70%, 2005: 79%, 2006: 76%, 2007: 75%, 2008: 74%, 2009: 76%, 2010: 74%; Switzerland was excluded because of missing data.
[18] Due to missing information regarding our output measures we were not able to include some important utilities like E.ON.
[19] See Kwoka (2002, 659f) for a discussion.
[20] To check for robustness, we ran all regressions presented in this paper without subtracting purchased power from total costs. Regression results hardly changed. This is especially true for the parameter of interest on the output interaction term (β_{GT}). Hence, the exclusion of purchased power seems less problematic in our analysis. One explanation may be that we focus on transmission unbundling, whereas the main body of the literature concentrates on distribution unbundling.

5.2. *Output variables*

The upstream *generation output* is measured as the *amount of electricity* (in GWh) produced in Europe. Even though some utilities operate at the national level only, others possess generation plants across countries. If an electricity utility is found to operate overseas (outside Europe), it was generally possible to obtain the amount of electricity produced in Europe.

We employ the *length of the transmission grid* (in kilometers) as a measure of the downstream *transmission output*.[21] This may seem controversial at first, but bears some advantages over a more conventional measure, such as transmitted volumes. Notably, the transmission grid is capital intensive and costs do not change with variations in transmitted volumes, in particular in the short run. Thus, contrary to transmitted volumes, the length of the transmission grid may be more accurate in capturing capital expenditures. Moreover, the length of the grid (besides other factors such as topography or underground cabling) is crucial for maintenance expenditures and thus may have an influence on operating expenditures. Another argument for measuring the transmission output variable in kilometers (rather than in GWh) is based on the fact that transmitted volumes may not be under the immediate control of transmission grid operators, while the lengths of the transmission lines are. Because of the laws of physics, electricity cannot be easily transmitted directly from one location to another, but rather flows through its way of least resistance – often via detours (called loop flows[22]) which are not subject to utilities' influence.

5.3. *Input price variables*

Among the input-price variables, we include the price of labor, the price of capital, and the price of fuel. The measurement of the price of labor is straightforward. It is calculated as the expenses on salaries per year divided by the number of employees and, thus, represents the average expenses per employee per year. The data are obtained from Worldscope and are supplemented and, in case of doubtful values, verified by data from Orbis or annual reports.

For the calculation of the price of capital we face one caveat. Generally, the annual rental rate of capital would represent a plausible measure. Nevertheless, we do not have such information for our sample. Therefore, we approximate this variable by the interest

[21] In the fashion of Triebs et al. (2012), we chose a single output measure (because of multi-collinearity issues) for the downstream transmission stage among several possibilities, such as transmission grid length, transmitted volumes, or peak grid-load.
[22] In general, loop flows play a minor role in the distribution network.

expenditures on long-term debt relative to long-term debt. Evidently, long-term debt represents the most important source of funds for a capital intensive industry like electricity.[23] The data come from Worldscope and are backed by Orbis und annual reports.

The price of fossil fuel is approximated by the annual average national price of natural gas for industrial customers obtained from OECD.[24] The utility's respective gas price was taken from the country of its headquarter. This seems plausible because most utilities in the sample operate to a large scale at the national level. Similarly, other studies have included the price of fossil fuel, generally approximated by the price of natural gas (e.g. Martínez-Budría, 2003; Jara-Díaz et al., 2004). Apart from fossil sources, other generation technologies, such as nuclear energy, water or other renewables, have very low or even zero fuel costs.[25]

5.3. Control variables

We employ the share of hydro (hyd) and the share of nuclear power (nuc) in total installed capacity per utility obtained from Platts PowerVison, in order to control for different generation techniques. Hydro and nuclear power exhibit low marginal costs and are therefore likely to serve as cost shifters. We expect a negative impact on total costs.

One decisive feature of this study is its sample of electricity utilities across European countries over time. Consequently, the panel structure allows employing fixed effects estimation in order to check for unobserved heterogeneity. Time fixed-effects are introduced to capture, for example, technological progress in the industry or other shocks such as demand variations (e.g. through the financial crisis) common to all utilities in the sample.

Given the limited number of 242 observations, firm fixed-effects estimation for all 28 sample utilities does not work properly. Supposedly, firm fixed-effects impose too many parameters and, hence, many parameter estimates turn out statistically insignificant. Therefore, we include country fixed-effects to take up unobserved heterogeneity across the 16 countries in

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[23] In a similar vein, Kaserman and Mayo (1991) employ the yield to maturity on long-term bonds as their price of capital, and Triebs et al. (2012) also concentrate on long-term interest rates for calculating capital expenditures.

[24] Unfortunately, the gas price explicitly for *electricity companies* in the OECD database exhibited too many missing values and could therefore not be employed in this analysis. However, both variables (i.e. the gas price for industrial customers and for electricity companies) reveal a high correlation of 0.998.

[25] The OECD Observer states that "unlike for coal, oil and gas, the impact on final prices of nuclear energy is very limited because fuel costs account for only 5% of the production cost." (OECD Observer No. 249, May 2005, http://www.oecdobserver.org/news/archivestory.php/aid/1595/Uranium_price_hike_.html, accessed 11 June, 2014).

the sample. These capture, for example, different regulatory regimes, climate conditions, which may determine demand for electricity, topography, relevant for the costs of constructing and maintaining the transmission grid, or production possibilities (e.g. availability of rivers for hydro power plants).

We also considered including other control variables, for example a measure of customer density. Nevertheless, this variable was not available. An approximation by the population density of the country of the firm's headquarter seemed problematic. The population density is likely to be related to the output variables. Indeed, regressions reacted sensitive to the inclusion of this variable.

5.4. General data issues

Financial variables, such as the total costs, salaries, or debt are obtained either from Worldscope for utilities listed on a stock exchange or from Orbis if not listed. Both sources provide data at the firm level. Accordingly, all global activities are captured if a firm operates overseas. This bears problems, since our output variables are measured at the European level.[26] For those utilities it was necessary to adjust their financial variables to European activities. Hence, we calculated the annual *share of sales in Europe in total (global) sales* for each firm that operated overseas and adjusted the financial variables accordingly.

Another data issue concerns the product mix of our sample utilities. Many electricity companies do not only provide a single product (electricity) but also engage in other production segments, foremost gas (but also water, waste, etc.). In order to limit our study to the analysis of *electricity*, it was necessary to adjust for firms' operations apart from electricity. Henceforth, we calculated the *share of revenues from electricity in total revenues (i.e. revenues generated from the whole product mix)* and corrected all financial variables and accordingly. Worldscope and Orbis provide their financial data on various operational segments (e.g. electricity). Moreover we checked for robustness with information from annual reports (and other external sources) when data were available.

[26] Of course, this is equal to the national level for utilities operating only within one country.

6. Results

This section provides regression estimates of the quadratic cost function as presented in Equation (2). Eventually, we utilize these estimates to quantify potential cost savings from vertical synergies between the stages of generation and transmission. Different specifications of the model are chosen and discussed against their appropriateness.

6.1. Cost function estimation

As presented in section 4, we impose linear homogeneity of the cost function and divide the costs and input prices by the price of fuel. Moreover, we apply Sheppard's Lemma to enhance estimation efficiency and estimate Equation (3) together with the cost share equations (4). In order to meet the non-linear characteristics of our cost function and its input shares, we estimate a non-linear system of equations. Hence, contrary to many other studies, which employ a linear estimator of the cost function, we apply non-linear GLS estimation (NLSUR), "which is the non-linear counterpart of the Zellner's iterated seemingly unrelated regression technique" (Fraquelli et al., 2005, p. 298).

As stated in the previous section, a particular feature of this analysis is the possibility of estimating a panel regression with fixed effects. Because of degrees of freedom considerations (given the limited number of 242 observations), we apply 16 country fixed-effects instead of 28 firm fixed-effects. Besides, we employ year fixed-effects. Country and year fixed-effects may capture unobserved regional (e.g. regulatory regimes, topography, production possibilities) and time heterogeneity (e.g. technological progress, demand shocks). This distinguishes our paper from many others.[27]

Table 2 shows the regression results from different model specifications. The basic model (Model i) excludes fixed effects, while alternative specifications introduce time fixed-effects (Model ii) and country fixed-effects (Model iii). Both time and country fixed-effects are included in Model (iv).[28] All regressions are estimated with robust standard errors. Evidently, the regression estimates are robust to different specifications. In line with our expectations, the introduction of additional fixed-effects leads to lower efficiency of the parameter

[27] We refer to Greene (2001) who states that fixed-effects estimation with non-linear models is feasible.
[28] Given space limitations, the coefficient estimates of the fixed effects are not reported, but are available upon request.

estimates (i.e. decreased statistical significance of some point estimates) because of lower degrees of freedom, but increases the overall fit (R^2).

Most importantly, the coefficient estimate on the output interaction term β_{GT} is negative and statistically significant across specifications. Given the discussion provided in Section 4 this indicates the presence of *variable* scope economies between the stages of generation and transmission (i.e. cost complementarity). Hence, with larger combinations of *both* outputs (i.e. larger amount of electricity generated and longer length of transmission grid lines), electricity utilities can realize cost savings. Variable cost synergies are therefore dependent on the magnitude of the two outputs. In section 6.2 we will compute the economic significance of these potential savings.

The overall constant (α_0) is positive and significant (except in Model iv). This is an indication that there exist fixed costs of operation which are independent of the magnitude of the outputs produced. For an integrated utility these fixed costs occur only once, but would be duplicated in case of separated production (which applies to unbundled utilities). Henceforth, the larger α_0 the larger potential cost savings from integrated operations of generation and transmission.

The parameter on stand-alone generation (α_G) measures the fixed costs of stand-alone generation compared to integrated operation of generation and transmission. However, the point estimate is statistically insignificant and hence not to be distinguished from zero. The positive and significant coefficient value for the separate constant on stand-alone transmission (α_T), in contrast, indicates potential fixed-cost increases for stand-alone transmitters from a duplication of operational tasks compared to joint supply of generation and transmission.

The full model specification including time and country fixed-effects (Model iv) provides robust parameter estimates compared to other specifications, yet suffers from a lower efficiency due to the high number of parameters imposed. The interesting parameter estimates on the fixed and variable cost synergies (α_0, β_{GT}, respectively) lose statistical significance. Nevertheless their point estimates are still in line with the other specifications, which estimate less parameters.

Although not explicitly shown in Table 2, the coefficient estimates of the time fixed-effects are largely insignificant, with the exception of significantly negative impacts in the years 2006 and 2007. In contrast, most country fixed-effects (10 out of 15 in Model iv) enter statistically significant. This points to significant heterogeneity across European countries with respect to the costs of supplying electricity.

5.1.Economies of vertical integration (EVI)

The quantification of vertical economies follows Equation (2) and is based on estimates from the cost function. Economies of vertical integration reflect the cost savings of joint operation of electricity generation and transmission versus stand-alone operation. Specifically, we calculate the cost savings from joint operation at various output percentiles. Since the generation output is zero below the 20th percentile and the transmission output below the 50th percentile, vertical synergies can only be computed for output combinations above these thresholds. Independent variables (input prices and control variables) are evaluated at their mean values. To obtain significance levels, we test Equation (2) against zero based on a non-linear Wald test.[29]

Table 3 reports the magnitude of vertical synergies at different output levels according to equation (2) and based on the estimates from the preferred NLSUR Model iv (see Table 2), which includes the full set of fixed effects. To check for robustness, we computed economies of vertical integration based on all alternative specifications, as shown in Models i–iii in Table 2. These results are provided in Table A2 in the appendix. All findings present similar values (except values at the corners; see footnote 30) indicating robustness to the specification of the cost function.

[29] We use STATA's command *testnl*. The p-values are based on the Delta-Method, which requires a large sample. Alternatively, we apply a linear test of Equation (1) against zero using STATA's command *lincom*. The significance levels hardly change.

Table 2. Non-linear regression (NLSUR) estimates of the cost function

	(i) Basic model			**(ii) Time FE**			**(iii) Country FE**			**(iv) Time & Country FE**		
α_0	0.5852	(0.003)	***	0.9311	(0.002)	***	1.0088	(0.022)	**	0.8026	(0.109)	
α_G	-0.1055	(0.591)		0.0385	(0.856)		-0.2736	(0.127)		-0.0071	(0.977)	
α_T	2.2536	(0.000)	***	2.2903	(0.000)	***	3.3830	(0.000)	***	3.2382	(0.000)	***
β_G	0.0351	(0.000)	***	0.0333	(0.000)	***	0.0596	(0.000)	***	0.0585	(0.000)	***
β_T	-0.1502	(0.000)	***	-0.1427	(0.000)	***	-0.1318	(0.001)	***	-0.1066	(0.011)	**
β_{GG}	0.0001	(0.070)	*	0.0002	(0.032)	**	0.0000	(0.926)		0.0000	(0.974)	
β_{TT}	0.0041	(0.001)	***	0.0038	(0.001)	***	0.0021	(0.064)	*	0.0014	(0.219)	
β_{GT}	-0.0006	(0.008)	***	-0.0007	(0.003)	***	-0.0007	(0.078)	*	-0.0008	(0.054)	*
γ_l	0.1789	(0.000)	***	0.1858	(0.000)	***	0.1679	(0.000)	***	0.1760	(0.000)	***
γ_c	0.3116	(0.000)	***	0.3230	(0.000)	***	0.3092	(0.000)	***	0.3189	(0.000)	***
γ_{ll}	-0.0078	(0.359)		-0.0110	(0.212)		-0.0045	(0.592)		-0.0085	(0.334)	
γ_{cc}	-0.1309	(0.000)	***	-0.1308	(0.000)	***	-0.1407	(0.000)	***	-0.1354	(0.000)	***
γ_{lc}	-0.0161	(0.001)	***	-0.0211	(0.000)	***	-0.0140	(0.007)	**	-0.0191	(0.000)	***
δ_{Gl}	0.0000	(0.745)		0.0000	(0.757)		0.0000	(0.630)		0.0000	(0.598)	
δ_{Gc}	-0.0007	(0.000)	***	-0.0007	(0.000)	***	-0.0006	(0.000)	***	-0.0006	(0.000)	***
δ_{Tl}	0.0006	(0.153)		0.0006	(0.161)		0.0006	(0.138)		0.0005	(0.152)	
δ_{Tc}	0.0042	(0.000)	***	0.0042	(0.000)	***	0.0041	(0.000)	***	0.0042	(0.000)	***
hyd	-0.0080	(0.002)	***	-0.0067	(0.016)	**	-0.0147	(0.037)	**	-0.0100	(0.182)	
nuc	-0.0063	(0.213)		-0.0053	(0.304)		0.0260	(0.189)		0.0252	(0.194)	
Time FE	no			yes			no			yes		
Country FE	no			no			yes			yes		
Obs.	242			242			242			242		
Overall R^2	0.883			0.891			0.928			0.936		

*Notes: Dependent variable is total expenditures excluding purchased power; Robust p-values in parentheses; ***, **, * indicate significance at the 1%, 5%, and 10% level respectively.*

Table 3 confirms the presence of substantial vertical cost synergies for European electricity utilities. The median electricity utility in our sample (evaluated at median output levels of 29,885 Gigawatt hours of generation and 658 kilometers of transmission lines) obtains cost savings from vertical integration of generation and transmission of around 13 percent relative to stand-alone operations. With larger output combinations, cost savings increase further. This is an indication that large electricity operators may benefit from higher economies of vertical integration. Yet, for very large output combinations, cost savings seem unrealistically high and should be viewed with caution.[30]

Table 3. Magnitude of economies of vertical integration (EVI) based on Model iv

Generation	Transmission GWh \ Km	50th %ile: 658		60th %ile: 3,657		70th %ile: 6,713		80th %ile: 11,000		90th %ile: 33,580	
20th %ile:	2,569	16.4%	**	17.6%	**	19.0%	**	21.2%	**	39.4%	***
30th %ile:	6,503	15.7%	**	17.0%	**	18.5%	**	20.8%	**	40.0%	***
40th %ile:	12,869	14.7%	**	16.1%	**	17.8%	**	20.3%	**	40.7%	***
50th %ile:	29,885	12.6%	**	14.3%	**	16.3%	**	19.3%	**	41.9%	***
60th %ile:	52,100	10.6%	*	12.7%	**	15.0%	**	18.5%	**	42.7%	**
70th %ile:	62,126	10.0%	*	12.1%	**	14.5%	**	18.2%	**	43.0%	**
80th %ile:	90,785	8.4%	*	10.9%	**	13.5%	**	17.5%	**	43.5%	**
90th %ile:	179,000	5.9%	*	8.8%	**	11.9%	**	16.5%	**	44.1%	**

*Notes: Calculation of EVI is based on Model iv, including time and country fixed effects. ***, **, * indicate significance at the 1%, 5%, and 10% level respectively. Values below the 20th percentile of generation and 50th percentile of transmission are not reported because outputs have values of zero. Cells in grey indicate output combinations at equal percentiles.*

Overall, vertical economies are found to be statistically and economically significant. In general, this analysis shows that the regulatory principle of ownership unbundling of the transmission grid comes at substantial costs due to lost vertical synergies. This finding holds especially true for large electricity utilities which may obtain cost advantages of beyond 15 percent.

The results presented in this section should be somehow viewed with caution, because the magnitude of economies of vertical integration may represent an upper bound of their true values. In our sample, stand-alone transmission companies are rather under represented compared to other organization forms, and hence cost synergies may be somehow overstated.

[30] The finding of large economies of scope near the corners of a cost function is quite common in the literature (e.g. Kwoka, 2002; Fraquelli et al., 2005; Fetz and Filippini, 2010). The reason is that the cost function as introduced in Equation (3) represents a Taylor approximation of the unknown true cost function. It may therefore only be suitable for estimation around the local minimum rather than near its corners. In our sample only one utility (i.e. EDF) exists in this scope.

Nevertheless, the results should be seen as an indication for the presence of substantial scope economies.

It may be of interest to decompose the findings on the cost synergies between the stages of generation and transmission into a *fixed* and a *variable* component. As indicated in Section 4, the fixed costs of joint production, measured by the overall constant, α_0, would be duplicated in case of vertical separation. In the Models i–iii, parameter estimates on α_0 are statistically significant suggesting that vertical divestiture is associated with significantly increased *fixed* costs of separated operations. Nevertheless, with lower degrees of freedom (because of more parameters or lower number of observations; Models iv–viii) α_0 becomes insignificant. Hence, *the presence of fixed cost synergies can be only partly confirmed*.

However, *the results provide strong evidence for the presence of variable cost synergies*, given the negative and statistically significant coefficient on the output interaction term β_{GT} across specifications. Hence, variable cost effects are crucial for the exploitation of vertical economies between the stages of electricity generation and transmission. This is an indication that vertically integrated utilities may be able to internalize negative market externalities through better coordination.

From those findings we can derive important policy implications. Countries with large vertically integrated electricity utilities prior to the implementation of ownership unbundling may suffer the most from vertical divestiture. To the contrary, countries with relatively small electricity companies may obtain economic benefits, such as non-discriminatory price competition in the upstream stage of generation, by introducing full ownership unbundling, while the associated losses from vertical economies may be of lesser importance.[31]

6. Conclusion and policy implications

The policy debate on transmission unbundling in Europe generally neglects the fact that the benefits of increased competition in the upstream stage of generation in the electricity sector come at the cost of destructing vertical synergies. One reason may be the absence of thorough empirical evidence for Europe. From this point, this analysis is, to the best of our knowledge,

[31] In this context, Meyer (2012b, 168) stresses that the actual degree of lost cost synergies from vertical divestiture largely hinges on the effectiveness of a newly created market mechanism that may overtake "firm internal coordination." However, we cannot empirically test for this hypothesis.

the first to provide European cross-country evidence on the costs of ownership unbundling of the transmission grid.

The EU has already put unbundling of the transmission grid from other stages of electricity supply into practice. Member States may choose between full ownership unbundling and the implementation of an ISO or ITO, where the first is the predominant form in Europe. The reason for transmission unbundling is the hope of increased competitive pressure in the upstream stage of electricity generation, caused by a separation from the transmission stage, which is associated with a natural monopoly. However, the potentially positive effects of transmission unbundling may be compensated or even offset by lost synergy effects.

Cost savings from vertical integration of generation and transmission are likely to arise from various effects. Among them are the common usage of inputs, such as capital and labor. Besides sharing of information and risk and coordination advantages are reasonable explanations for cost savings. Hence, ownership unbundling of generation and transmission may result in significantly higher costs for utilities in Europe.

This study implements novel firm-level data on 28 major European electricity utilities from 16 European countries over the period 2000–2010. Data emanate from annual reports as well as Worldscope, Orbis, Platts PowerVision, and OECD. One decisive feature of this paper is that the inclusion of (time and country) fixed-effects to account for unobserved heterogeneity.

Based on the empirical estimation of a quadratic cost function, we quantify vertical economies of scope. Contrary to many other related studies, we introduce a fully specified cost function (including a full set of output and input price interaction terms) together with its input share equations (Sheppard's Lemma) and all standard assumptions (i.e. linear homogeneity in input prices and symmetry in parameters). In order to meet the non-linearity characteristics of the system of equations, we apply a non-linear GLS estimator (NLSUR).

The results of this analysis confirm that there exist substantial scope economies between the stages of upstream generation and downstream transmission in Europe. For the median firm in our sample we find cost savings from vertical integration of around 13 percent. There are further potential cost savings to be generated at greater output levels. Therefore, larger operators may exhibit larger vertical economies in the scope of 15 to 20 percent. This may be explained by the fact that *variable* cost synergies are found to be economically and statistically significant across specifications. Additionally, there is some indication that fixed cost synergies are of relevance. In general, the results are robust to different specifications.

Against the above, one policy implication may be that countries with large vertically integrated electricity operators are the ones which face the most severe costs of introducing ownership unbundling of the transmission grid. Therefore, such countries (e.g. France or Germany) which have not yet implemented transmission ownership unbundling, may be confronted with substantial costs by such a new policy. Given the high complexity of the electricity market and the interdependency of its supply stages introduces limitations to regulation (such as the implementation of the unbundling principle). Although we do not investigate this issue explicitly, there is some evidence that legal unbundling may serve as a reasonable compromise between the two extremes of vertical integration and full ownership unbundling (e.g. Höffler and Kranz, 2011; Pollitt, 2008).

One should keep in mind that this analysis has a rather static focus because the data at hand do not allow for a proficient analysis of dynamic effects. Over time, cost increases may be partly compensated by positive dynamic effects of unbundling.[32] Besides, the estimated additional costs of ownership unbundling through lost vertical synergies cannot be easily compared with the benefits of increased competition and anti-monopolistic forces. This analysis represents, however, an important contribution to the literature and general debate on unbundling, as it provides evidence that transmission ownership unbundling comes at a cost, which has to be addressed in the policy debate. Overall, more empirical research on the costs and benefits of ownership unbundling is needed. Moreover, an empirical investigation of different unbundling regimes (e.g. legal vs ownership) would be of great interest.

[32] Schober (2013) provides a comparison of static versus dynamic effects of distribution unbundling. His finds that negative static effects from ownership unbundling and third party access are eventually offset by positive dynamic effects.

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Appendix

Table A1. Sample of electricity utilities

utility	Country	Obs.	Period	Organizational structure
EVN	Austria	11	2000-2010	G
Verbund	Austria	11	2000-2010	G&T
Wiener Stadtwerke	Austria	3	2008-2010	G
CEZ Group	Czech Rep.	11	2000-2010	G&T until 2002, then G
Fortum	Finland	10	2001-2010	G
EDF	France	11	2000-2010	G&T
ENBW	Germany	10	2001-2010	G&T
RWE	Germany	11	2000-2010	G&T
Public Power Corp.	Greece	11	2000-2010	G&T
Magyar Villamos	Hungary	7	2003-2010	G&T
A2A	Italy	7	2004-2010	G
Acea	Italy	11	2000-2010	G&T until 2005, then G
Enel	Italy	6	2005-2010	G
IREN	Italy	11	2000-2010	G&T
Terna	Italy	10	2001-2010	T
Latvenergo	Latvia	5	2006-2010	G&T
Statkraft	Norway	5	2006-2010	G
Enea	Poland	3	2008-2010	G
PGE Polska Grupa	Poland	3	2008-2010	G
EDP	Portugal	10	2001-2010	G&T
Endesa	Spain	11	2000-2010	G
Iberdrola	Spain	9	2002-2010	G
Red Electrica	Spain	8	2003-2010	T
Vattenfall	Sweden	10	2001-2010	G&T until 2009, then G
BKW	Switzerland	11	2000-2010	G&T
Energiedienst	Switzerland	7	2004-2010	G&T
Drax Group	United Kingdom	8	2003-2010	G
National Grid	United Kingdom	11	2000-2010	T
Total		*242*		

Notes: Obs. Is observations; G&T represents an integrated utility, G is stand-alone generation, T is stand-alone transmission.

Table A2. Magnitude of economies of vertical integration (EVI)

Panel A. EVI based on Model i (excl. FE)

Generation	Transmission GWh \ Km	50th %ile: 658		60th %ile: 3,657		70th %ile: 6,713		80th %ile: 11,000		90th %ile: 33,580	
20th %ile:	2,569	17.7%	***	20.5%	***	23.9%	***	30.0%	***	96.3%	**
30th %ile:	6,503	17.0%	***	19.8%	***	23.2%	***	29.3%	***	89.2%	***
40th %ile:	12,869	16.0%	***	18.8%	***	22.2%	***	28.2%	***	81.5%	***
50th %ile:	29,885	13.8%	***	16.6%	***	20.0%	***	25.8%	***	70.2%	***
60th %ile:	52,100	11.6%	***	14.5%	***	17.9%	***	23.5%	***	62.7%	***
70th %ile:	62,126	10.8%	***	13.7%	***	17.1%	***	22.7%	***	60.3%	***
80th %ile:	90,785	8.9%	***	11.9%	***	15.3%	***	20.7%	***	55.2%	***
90th %ile:	179,000	5.6%	***	8.6%	***	11.8%	***	16.7%	***	45.5%	***

Panel B. EVI based on Model ii (incl. time FE)

Generation	Transmission GWh \ Km	50th %ile: 658		60th %ile: 3,657		70th %ile: 6,713		80th %ile: 11,000		90th %ile: 33,580	
20th %ile:	2,569	17.7%	***	20.5%	***	23.9%	***	30.0%	***	96.3%	**
30th %ile:	6,503	17.0%	***	19.8%	***	23.2%	***	29.3%	***	89.2%	***
40th %ile:	12,869	16.0%	***	18.8%	***	22.2%	***	28.2%	***	81.5%	***
50th %ile:	29,885	13.8%	***	16.6%	***	20.0%	***	25.8%	***	70.2%	***
60th %ile:	52,100	11.6%	***	14.5%	***	17.9%	***	23.5%	***	62.7%	***
70th %ile:	62,126	10.8%	***	13.7%	***	17.1%	***	22.7%	***	60.3%	***
80th %ile:	90,785	8.9%	***	11.9%	***	15.3%	***	20.7%	***	55.2%	***
90th %ile:	179,000	5.6%	***	8.6%	***	11.8%	***	16.7%	***	45.5%	***

Panel C. EVI based on Model iii (incl. country FE)

Generation	Transmission GWh \ Km	50th %ile: 658		60th %ile: 3,657		70th %ile: 6,713		80th %ile: 11,000		90th %ile: 33,580	
20th %ile:	2,569	19.5%	***	21.1%	***	23.0%	***	26.0%	***	52.3%	***
30th %ile:	6,503	18.7%	***	20.3%	***	22.3%	***	25.3%	***	51.2%	***
40th %ile:	12,869	17.5%	***	19.2%	***	21.2%	***	24.3%	***	49.9%	***
50th %ile:	29,885	15.0%	***	16.9%	***	19.1%	***	22.4%	***	47.6%	***
60th %ile:	52,100	12.7%	**	14.8%	***	17.2%	***	20.8%	**	46.1%	**
70th %ile:	62,126	11.9%	**	14.1%	**	16.5%	**	20.2%	**	45.6%	**
80th %ile:	90,785	10.1%	**	12.5%	**	15.1%	**	19.0%	**	44.8%	**
90th %ile:	179,000	7.1%	**	9.8%	**	12.8%	**	17.2%	**	43.9%	**

*Notes: Calculation of EVI is based on Model iv, including time and country fixed effects. ***, **, * indicate significance at the 1%, 5%, and 10% level respectively. Values below the 20th percentile of generation and 50th percentile of transmission are not reported because outputs have values of zero. Cells in grey indicate output combinations at equal percentiles.*