



HAL
open science

Quality of Service, Efficiency, and Scale in Network Industries: An Analysis of European Electricity Distribution

Christian Growitsch, Tooraj - Jamasb, Michael Gerald Pollitt

► **To cite this version:**

Christian Growitsch, Tooraj - Jamasb, Michael Gerald Pollitt. Quality of Service, Efficiency, and Scale in Network Industries: An Analysis of European Electricity Distribution. *Applied Economics*, 2009, 41 (20), pp.2555-2570. 10.1080/00036840701262872 . hal-00582129

HAL Id: hal-00582129

<https://hal.science/hal-00582129>

Submitted on 1 Apr 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Quality of Service, Efficiency, and Scale in Network Industries: An Analysis of European Electricity Distribution

Journal:	<i>Applied Economics</i>
Manuscript ID:	APE-06-0294
Journal Selection:	Applied Economics
JEL Code:	L15 - Information and Product Quality Standardization and Compatibility < L1 - Market Structure, Firm Strategy, and Market Performance < L - Industrial Organization, L51 - Economics of Regulation < L5 - Regulation and Industrial Policy < L - Industrial Organization, L94 - Electric Utilities < L9 - Industry Studies: Transportation and Utilities < L - Industrial Organization
Keywords:	efficiency, quality of service, scale economies, input distance function, stochastic frontier analysis

powered by ScholarOne
Manuscript Central™

Quality of Service, Efficiency, and Scale in Network Industries: An Analysis of European Electricity Distribution

Abstract

Quality of service is of major economic significance in natural monopoly infrastructure industries. In this paper we present an efficiency analysis of electricity distribution networks from seven European countries. We apply the stochastic frontier analysis (SFA) method on multi-output translog input distance function models to estimate cost efficiency and scale economies. We show that introducing the quality dimension into the analysis affects estimated efficiency significantly, especially that smaller utilities' efficiency seems to decrease. Our results emphasise that quality of service should be an integrated part of efficiency analysis and in the economic review in regulated natural monopolies.

Keywords: efficiency, quality of service, scale economies, input distance function, stochastic frontier analysis.

JEL: L15, L51, L94

1. Introduction

Infrastructure industries, such as electricity, telecommunications, gas, transport, and water continue to maintain their strategic importance in modern economies. Since the 1990s, the globally dominant paradigms governing the structure and ownership models of these industries, natural monopoly, vertical integration, and public ownership, have been challenged. Liberal models based on competition, economic incentives, and private ownership have been adopted to achieve internal and external efficiency improvements in these sectors and to benefit customers in the form of lower costs and higher service quality.

The electricity sector has witnessed considerable liberalisation activities in many countries around the world. The main tenets of electricity sector liberalisation have been restructuring, regulation, and privatization. Implementing the new model required restructuring of the industries to separate potentially competitive segments (generation and retail supply) from natural monopoly activities (distribution and transmission) that would need to be regulated. Independent regulation would oversee the successful functioning of competitive power markets and regulated transmission and distribution networks. Private ownership and profit incentive would promote internal efficiency in the firms. Moreover, two important aspects of the new industry structure have been widely neglected: the question of (efficient) optimal firm size in natural monopolies and its relation to quality of service (QoS).

In competitive markets, competition and market size are important determinants of firm size and market concentration (subject to rules and policy). In natural monopolies, in the absence of market forces, public intervention, regulation, and history are often factors that affect efficiency and scale of firms. Theory characterises natural monopolies to be the most technically efficient market structure when a single firm can produce a specific output vector at less cost than two or more firms (subadditivity). Subadditive cost structures have been theoretically and empirically shown in networks of infrastructure industries (e.g. Gilsdorf, 1995 and Salvanes and Tjøtta, 1998). However, the appropriate scale (of production) of natural monopolies is also of economic interest. Optimal firm size as well as technical efficiency is related to the underlying production technology

1
2
3 and structure of an industry. Therefore, in any given industry, the relationship between
4 efficiency and scale is an empirical question.
5
6

7
8 In the context of European electricity sector reform, the natural monopoly characteristics
9 and economic importance of firm size and quality of service in distribution networks has
10 led to public intervention and regulation in these activities. First, at the time of
11 restructuring and unbundling, political decision-makers were faced with decisions
12 regarding the number and size of firms. Second, in the post-reform period since the end
13 of the 1990s, mergers and acquisitions – vertically and horizontally – increased market
14 concentration dramatically and changed the size of the firms requiring an informed
15 policy towards this development.¹ At the same time, the desirability of having a large
16 number of utilities in small countries (e.g. Nordic countries) poses an interesting policy
17 question. Third, adoption of incentive regulation models in recent years has given rise to
18 concerns that, if left unregulated, the pursuit of profit maximisation is likely to result in
19 deterioration of quality of service.
20
21
22
23
24
25
26
27
28
29

30 In particular, a formal treatment of QoS from an industrial organisation point of view
31 and/or as an integrated part of regulatory analysis has been widely neglected. This is
32 especially problematic as there are interactions and trade-offs between utilities' costs
33 (capital as well as operating and maintenance expenditures) and their size and quality of
34 services. A simple cost-only approach to efficiency in regulated utilities will, therefore,
35 not take an essential aspect of their activities into account. It is conceivable that quality-
36 incorporated efficiency and scale measures of firms might differ from those of a cost-
37 only approach. It is therefore important to enhance understanding of the significance of
38 quality of service for efficiency and scale in network industries. Specifically, it might be
39 that small operations are justified even where they have high costs but provide higher
40 service quality and vice versa.
41
42
43
44
45
46
47
48
49
50

51 This paper aims to fill the void in previous research and shed some empirical light on
52 the effects of including quality dimensions into the analysis of technical efficiency and
53 optimal firm size. We estimate technical efficiency and scale economies of a sample of
54
55
56
57

58
59 ¹ For an overview of mergers and acquisitions activity in the European electricity supply industry, cp.
60 Codognet et al (2002).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

about 500 electricity distribution utilities from seven European countries, applying stochastic frontier analysis (SFA) method and multi-output translog input distance function models. The outline for the remainder of this paper is as follows. The theoretical foundations and previous literature are presented in Section 2. Section 3 discusses the methodology, and the estimation method. In Section 4 we introduce the modelling approach and specify the estimated models. The data is described in Section 5. Estimation results are presented in Section 6. Section 7 contains conclusions and highlights policy implications and directions for future research.

2. Efficiency and Quality of Service

The nature of electricity distribution has been examined in a number of theoretical and empirical studies, which predominantly support the existence of natural monopoly conditions in distribution networks.² This section recapitulates the basic conditions of natural monopoly theory and reviews previous research on (international) productivity analysis, optimal firm size, and on quality of service in network industries. We then present two hypotheses regarding the relationship between quality of service, technical efficiency, and firm size in electricity distribution networks.

The natural monopoly characteristics in electricity distribution can be attributed to three major aspects (e.g. Growitsch and Wein 2004): the high degree of sunk investments in network assets (e.g. power lines and transformers), economies of scale in electricity supply, and economies of scope between the major services in electricity distribution, namely ‘customer connection’ and ‘energy delivery’.³ In economic theory, a natural monopoly is described as a market structure, where it is technically efficient to produce a certain output vector by a single firm. Technically, this condition occurs if the cost structure of such a market is strictly and globally subadditive for all output vectors Y^i , $i = 1, \dots, m$:

2 For example, *Gilsdorf* (1994, 1995), *Filippini* (1998), *Salvanes and Tjøtta* (1998), and *Yatchew* (2000).

3 For a detailed description of outputs in electricity distribution, see Section 4.

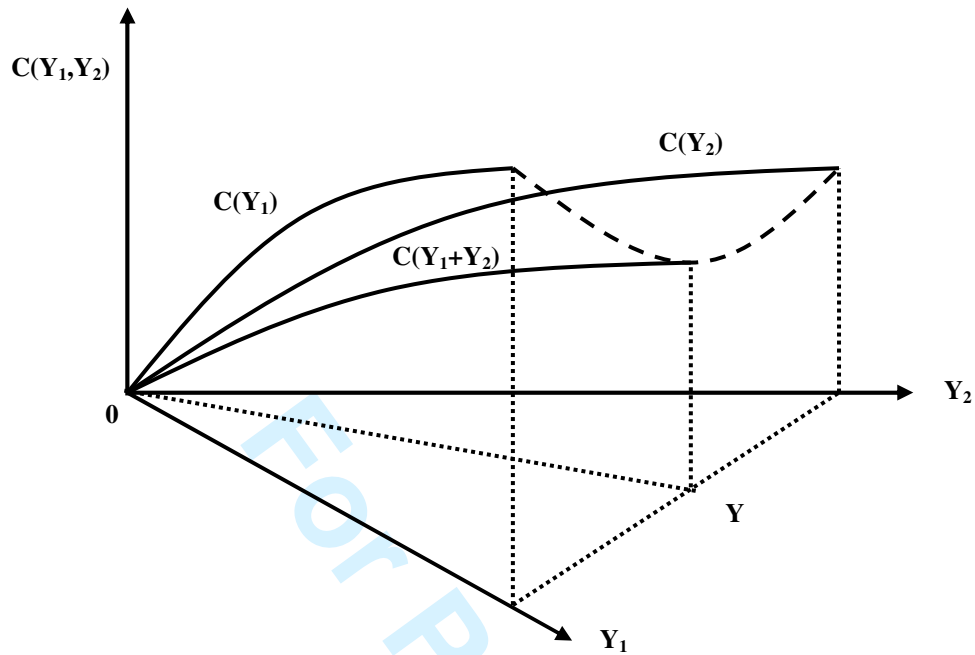
$$C\left(\sum_{i=1}^m Y^i\right) \leq \sum_{i=1}^m C(Y^i) \quad (1)$$

In the case of a single-product firm, economies of scale (declining average costs) and concavity (falling marginal costs) are sufficient conditions for subadditivity and therefore existence of natural monopoly.⁴ Baumol (1977) and Baumol et al. (1982) first discussed the economic concept of natural monopoly in the context of multi-product industries. In multi-output settings, economies of scale and the related property of declining-ray average costs are neither necessary nor sufficient for subadditivity of cost functions. Instead, in the multi-output context, subadditivity also requires presence of economies of joint production, either in the form of cost complementarity or trans-ray convexity.⁵ Cost complementarity holds if inequality 1 is true for incremental as well as for total costs (Sharkey, 1982). Figure 1 illustrates the concept of transray convexity (here: in connection with economies of scale both in separate and joint production of outputs Y_1 and Y_2). A cost function C for two outputs Y_1 and Y_2 satisfies the property of transray convexity at a point Y if a line through Y shows a negative slope proving economies of joint production. The joint production cost function $C(Y_1+Y_2)$ in Figure 1 is also concave along all rays through the origin, indicating additional economies of scale. Being concave and transray convex, the illustrated cost function satisfies sufficient conditions of subadditivity.

4 *Sharkey* (1982) presents numerous examples of subadditive cost functions to illustrate that neither economies of scale nor concavity are necessary conditions for subadditivity. As the existence of natural monopoly conditions in electricity distribution is an established notion, we are going to concentrate on more straightforward calculations rather than hypothetical exceptions.

5 See *Baumol* (1977) and *Baumol et al.* (1982) for a detailed description of these concepts and sufficient conditions for natural monopolies.

Figure 1:
Subadditivity in the two-output case



Applying the concept of multi-output production in natural monopolies to electricity distribution we focus on analysis of multi-product economies of scale (which is equivalent to identifying concavity of the joint cost function in Figure 1), testing for existence of economies of joint production, namely economies of scope (which is transray convexity in Figure 1). This is appropriate, as the aim of this study is to examine optimal utility/service size and the natural monopoly characteristics of electricity distribution networks are well-established. Although, there is ample evidence that there is considerable variation in efficiency of distribution utilities (e.g. IPART 1999, Jamasb and Pollitt 2003), the effects of size and quality of service on efficient operation and performance of these utilities is less clear.

The reviewed literature points to different economic and methodological aspects that are related to the subject matter of this paper. First, a branch of studies has focused on international comparisons of network industries including electricity distribution. Second, there is a line of literature that analyses most productive scale size in electricity distribution. Third, a limited body of literature has addressed the issue of quality of service aspect in network industries.

1
2
3 Academic research and, to a lesser extent, regulation has used cross-country efficiency
4 analyses partly to overcome problems due to a small number of observations, cross-
5 border mergers, or/and the possibility of collusion among the regulated companies
6 (Jamasp and Pollitt, 2003; Estache et al., 2004). Regulatory use of efficiency analysis
7 has largely been limited to single country analysis. Cross-country studies of the
8 performance of electric utilities are, however, rather few. In a comparison of UK and US
9 distribution utilities, Pollitt (1995) finds a comparable performance in both countries.
10 IPART (1999), in a study for the Independent Pricing and Regulatory Tribunal in
11 Australia focuses primarily on Australian distribution companies, taking UK and New
12 Zealand utilities as additional observations. In another comparison of seven Australian
13 and 32 international electricity utilities Whiteman (1995) uses an international reference
14 set to analyse the development of X-inefficiency in Australian electricity utilities.
15
16
17
18
19
20
21
22
23
24
25

26 In a comparison of Scandinavian and Dutch electricity distribution companies,
27 Edvardsen and Førsund (2003) show the advantage of international comparisons in
28 identifying peer companies. Jamasp and Pollitt (2003) compare the efficiency of 63
29 distribution utilities from six European countries using parametric and non-parametric
30 benchmarking methods. They find that efficiency results tend to be rather sensitive in
31 level, although not in rank order. Additionally, they report methods of introducing
32 comparability in international samples. Analysing panel data of 84 South American
33 electricity distributors from eight countries, Estache et al. (2004) point out the
34 importance of international benchmarking and the coordination of regulators in order to
35 reduce information asymmetries. In a recent study, Hattori et al. (2005) analyse the
36 efficiency development of UK and Japanese distribution utilities using panel data from
37 1985-1998, reporting an acceleration of productivity growth over time and positive
38 economies of scale for UK companies relative to Japanese firms.
39
40
41
42
43
44
45
46
47
48
49

50 Previous research on scale economies and optimal firm size commonly applies the Data
51 Envelopment Analysis (DEA) technique to calculate the scale efficiency by comparing
52 the efficiency results from constant and variable returns to scale models.⁶ Empirical
53 results from parametric models tend to be rather few and predominantly applied cost
54
55
56
57
58

59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000

6 For an introduction see *Coelli et al.* (1998).

1
2
3 functions for the analysis. For electricity distribution, an early contribution was by
4 Nerlove (1963), who applies a cost function based on a generalized Cobb-Douglas
5 production function and gives evidence for the possibility of substitution among factors
6 of production. In two studies of Swiss electricity distribution utilities, Filippini (1996)
7 and Filippini and Wild (2001) using a flexible translog and a linear average cost
8 function find evidence of increasing returns to scale throughout their sample of 39 and
9 59 utilities respectively.

10
11
12
13
14
15
16
17 Other studies address the issue of minimum efficient scale size. Giles and Wyatt (1993)
18 estimate a total cost function from a sample of 60 New Zealand electricity distributors,
19 reporting an efficient scale for a sales range of 500 to 3500 GWh. Yatchew (2000)
20 converted the results from Giles and Wyatt on a number of customer basis and reports a
21 minimum efficient scale size at 30000 customers. Salvanes and Tjøtta (1994) in a cross-
22 sectional analysis of 100 Norwegian electricity distribution utilities find an optimal firm
23 size at about 20,000 customers and that is relatively independent from the GWh sales.
24 These results confirm Yatchew's (2000) findings based on a four-year panel of 81
25 Canadian distributors. The study estimated a semi-parametric translog cost function and
26 reports substantial scale economies and a minimum efficient scale achieved by firms
27 with about 20000 customers.

28
29
30
31
32
33
34
35
36
37
38 Empirical research on quality of service in network industries is scarce and mostly
39 concentrated on telecommunications sector (Resende and Façanha, 2004; Sappington,
40 2002; Ai and Sappington, 1998; Kridel et al., 1996). For the electricity sector, Ter-
41 Martirosyan (2003) analyses the effect of incentive regulation on duration and frequency
42 of electric outages for a panel of 78 U.S. utilities, reporting an increase in the duration of
43 outages associated with incentive regulation. The study also finds that outages decrease
44 when explicit quality benchmarks are introduced. Korhonen and Syrjänen (2003) find
45 improvement in technical efficiency after incorporating quality of service (interruption
46 time per customer) in their DEA analysis of 106 Finish distribution utilities. CEPA
47 (2003) applies a two step DEA model to cross-sectional data for the UK and finds no
48 significant correlation between technical efficiency measures and service quality in
49 terms of minutes lost per customer. Ajodhia et al. (2004) apply a DEA and a Corrected
50 Ordinary Least Squares (COLS) model to a cross-sectional sample of 44 electric utilities
51
52
53
54
55
56
57
58
59
60

1
2
3 from four countries (UK, Netherlands, Hungary and Malaysia), reporting a significant
4 efficiency increase when quality is taken into account especially for smaller utilities.
5 Giannakis et al. (2005) carried out a quality incorporated efficiency study with panel
6 data on UK electricity distribution. They show that technical efficiency does not
7 necessarily also involve high service quality and state that quality incorporated
8 regulatory benchmarking is superior to cost-only approaches.
9

10
11
12 The relationship of efficiency, firm size, and quality in regulated network industries has
13 not been addressed previously. Kwoka (2005) is an exception, who in an analysis of
14 private and public U.S. electric utilities estimates a quadratic cost function and reports
15 lower distribution costs and higher quality in terms of lower duration of interruptions for
16 smaller (public) companies. However, he did not apply frontier analysis and was not
17 able to measure individual company efficiency.
18

19
20 Our review of natural monopoly theory and previous studies on electricity distribution
21 suggests that important aspects of industry structure have not been addressed. The first
22 issue is the relationship between technical efficiency and firm size. Insofar as economies
23 of scale exist, larger firms are expected to demonstrate higher technical efficiency
24 ceteris paribus. This relationship also applies to economies of scope between outputs
25 (e.g. customer numbers and energy supplied). Natural monopoly theory would then
26 suggest increasing service area size until scale economies are exploited.
27

28
29 Inclusion of the quality dimension into technical efficiency analysis might alter the
30 optimal firm size. Kwoka presents the hypothesis, that smaller utilities supply higher
31 quality, as they have easier access to local market and customer specific information
32 (such as demand characteristics and special technical conditions), being important for
33 service quality and reliability. Moreover, organizational aspects such as multiple
34 objectives combined with observability of results and measurement problems in large
35 firms can explain higher quality of service in small firms (Holmström, 1989 and Dixit,
36 1997). In addition, quality criteria are difficult to specify and to enforce (Kwoka, 2005).
37 Also, it has been argued that closeness to customer leads to higher quality of service.⁷ If
38
39

40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
⁷ However, it should be mentioned that some degree of self-selection may exist as small firms with low quality of service may have gradually been acquired by larger and more efficient firms.

1
2
3 the above proposition holds, incorporating quality of service in electricity distribution
4 utilities' production function and technical efficiency measurement could reduce
5 economies of scale and decrease optimal utility size relative to a pure cost analysis. The
6 following two main hypotheses can be drawn:
7
8
9

- 10
11 (i) In a pure cost efficiency analysis, the natural monopoly characteristics
12 (economies of scale and scope) in electricity distribution can be assumed to
13 produce a higher efficiency associated with firm size (*'economies of scale'*
14 *hypothesis*).
15
16
17
18
19 (ii) The relative cost and efficiency advantage of large firms declines when quality
20 of service is taken into account. (*'proximity to customers' hypothesis*).
21
22
23

24 We test these hypotheses by applying stochastic frontier analysis and distance functions
25 to examine the technical efficiency, scale economies and scope economies of electricity
26 distribution utilities using a pure cost and combined cost-quality analysis.
27
28
29
30
31

32 **3. Methodology**

33
34
35 Shephard (1953, 1970) proposed the distance function approach for specifying the
36 production technology of a multi-output multi-input firm. When analysing regulated
37 industries this approach has advantages over cost or revenue functions since the
38 behavioural assumptions of the latter approaches are likely to be violated (Estache et al.,
39 2004).⁸ Distance functions can be differentiated into input and output distance
40 functions. The former describes the maximum radial contraction of the input vector
41 while keeping the output vector constant. The latter gives information about the
42 maximum producible output given an input vector. For the purpose of this study, we use
43 the input distance function approach as outputs of electricity distribution networks are
44 exogenously determined due to the derived nature of demand (i.e. that is distribution of
45 a given amount of energy demanded to a given number of customers) for their output.
46
47
48
49
50
51
52
53
54
55
56

57
58
59 ⁸ Estache et al. (2004) refer to a violation of standard assumptions (for example profit maximisation or
60 efficient production) in production economics due to regulation and public ownership.

The input distance function summarizing all economically relevant characteristics of the production technology can be defined as

$$D^I(X, Y) = \max\{\rho : (X/\rho) \in L(Y)\} \quad (2)$$

where the input set $L(Y)$ represents the set of all input vectors X that can produce outputs Y . We assume this production technology satisfies the properties discussed in Färe and Primont (1995). From $X \in L(Y)$ follows that $D^I(X, Y) \geq 1$, equalling unity for any company on the frontier of the input set. The input distance function has some additional properties, it is linear homogenous and concave in X . The translog (transcendental logarithmic) functional form, originally introduced as a cost function model by Christensen et al. (1973), has several virtues, which apply to a distance function as well (Kumbhakar and Lovell, 2000). The translog input distance function is flexible and allows imposition of assumptions from microeconomic theory such as homogeneity, symmetry and monotonicity.

When defined for the case of K inputs and M outputs, the translog input distance function is specified as

$$\begin{aligned} \ln D_i^I = & \alpha_0 + \sum_{m=1}^M \alpha_m \ln y_{mi} + \frac{1}{2} \sum_{m=1}^M \sum_{n=1}^M \alpha_{mn} \ln y_{mi} \ln y_{ni} \\ & + \sum_{k=1}^K \beta_k \ln x_{ki} + \frac{1}{2} \sum_{k=1}^K \sum_{l=1}^K \beta_{kl} \ln x_{ki} \ln x_{li} + \frac{1}{2} \sum_{k=1}^K \sum_{m=1}^M \delta_{km} \ln x_{ki} \ln y_{mi} \end{aligned} \quad (3)$$

with α , β and δ being parameters to be estimated and i denoting the i th firm of the sample. To impose the properties proposed by microeconomic theory, some constraints on the unknown parameters are required. Symmetry is given if the second order coefficients satisfy

$$\beta_{kl} = \beta_{lk} \quad \text{and} \quad \alpha_{mn} = \alpha_{nm} \quad \text{for } k = 1, 2, \dots, K \text{ and } m = 1, 2, \dots, M. \quad (4)$$

The restrictions required for homogeneity of degree + 1 in inputs are

$$\sum_{k=1}^K \beta_k = 1, \sum_{l=1}^K \beta_{kl} = 0, k = 1, 2, \dots, K \text{ and } \sum_{m=1}^M \delta_{km} = 0, m = 1, 2, \dots, M. \quad (5)$$

The monotonicity constraint is satisfied if and only if

$$\frac{\partial \ln D^I}{\partial \ln x_k} = \beta_k + \sum_{l=1}^K \beta_{kl} x_l + \sum_{m=1}^M \delta_{km} y_m \geq 0. \quad (6)$$

and

$$\frac{\partial \ln D^I}{\partial \ln Y_m} = \alpha_m + \sum_{n=1}^M \alpha_{mn} y_n + \sum_{k=1}^K \delta_{km} x_k \leq 0. \quad (7)$$

Based on the above formalisation, it is possible to calculate additional economic characteristics of the corresponding technology. A focal point of this study is the analysis of optimal firm size. As shown above, this is related to scale elasticities and returns to scale, which can be obtained from the input distance function as shown by Färe and Primont (1995). For the multi-output case, returns to scale can be defined as follows:

$$RTS = \frac{-1}{\nabla D^I(y, x)y}. \quad (8)$$

where $\nabla D^I(y, x)$ is the vector of first order partial derivatives of the distance function with respect to outputs (Rungsuriyawiboon and O'Donnell, 2004). Values of RTS greater than one indicate increasing returns to scale, whereas values smaller than one imply decreasing returns to scale. The optimal firm size is where RTS equals unity; constant returns to scale are a necessary and sufficient condition for optimal scale size in electricity distribution. Nevertheless, there is a distinction between scale economies and scale efficiency. The latter is, in a parametric setting, equivalent to the ray average productivity at the observed input bundle relative to the constant returns to scale input

vector and differs from the scale economy value except for bundles of constant returns to scale (Morrison-Paul et al., 2004).⁹ We calculate the returns to scale as the negative inverse of the scale elasticities: the (negative) scale elasticity is defined as the sum of production elasticities:

$$-\mathcal{E}_{DIY} = -\sum_m \frac{\partial \ln D^I}{\partial \ln y_m}. \quad (9)$$

As Morrison-Paul et al. (2004) state, this formula is consistent with Equation 8 and conceptually comparable to the multi-output cost elasticities in Baumol et al. (1982).

Indeed, this measure of multi-product scale elasticities includes economies of joint production. Denny and Pinto (1978) showed that economies of joint production (scope economies) exist in translog functions if $-\alpha_m * \alpha_n < \alpha_{mn}$. To control for joint production effects, we impose the constraint $\alpha_{mn} = -\alpha_m * \alpha_n$ into the scale elasticity formula and calculate a net scale elasticity measure. Subtracting net scale elasticity from the scale elasticity defined in formula 9 gives a measure of economies of scope.

Atkinson and Primont (2002) show that it is possible to calculate ‘implicit input value shares’ (Rungsuriyawiboon and O’Donnell, 2004) for any input k by

$$\frac{\partial \ln D^I}{\partial \ln x_k} = \frac{x_k}{D^I} \frac{\partial D^I}{\partial x_k}. \quad (10)$$

Ratios of these derivatives can be interpreted as a unit-less rate of input substitution (Rungsuriyawiboon and O’Donnell, 2004).

In order to estimate firm specific technical efficiency, we apply stochastic frontier analysis (SFA), originally introduced by Aigner et al. (1977) and Meeusen and van den Broeck (1977). SFA is a parametric method which can also estimate an efficient or best practice frontier from a distance function model and firm specific deviations (i.e. inefficiency) from the frontier in the form of technical efficiency scores (see e.g. Coelli

⁹ See Ray (1999, 2003), Balk (2001), and Orea (2002) for more detailed discussions.

et al. 1998). The estimated technical efficiency scores range between 1 and 0 where a score of 1 means that a firm is the most efficient in the sample and is on the efficient frontier while 0 represents the least efficiency.

Imposing the restrictions specified above, a stochastic frontier model of firm i can be modelled as follows (Coelli and Perelman 1999, Rungsuriyawiboon and O'Donnell, 2004):

$$\begin{aligned}
 -\ln(x_{Ki}) = & \\
 & \alpha_0 + \sum_{m=1}^M \alpha_m \ln y_{mi} + \frac{1}{2} \sum_{m=1}^M \sum_{n=1}^M \alpha_{mn} \ln y_{mi} \ln y_{ni} \\
 & + \sum_{k=1}^{K-1} \beta_k \ln \left(\frac{x_{ki}}{x_{Ki}} \right) + \frac{1}{2} \sum_{k=1}^{K-1} \sum_{l=1}^{K-1} \beta_{kl} \ln \left(\frac{x_{ki}}{x_{Ki}} \right) \ln \left(\frac{x_{li}}{x_{Ki}} \right) \\
 & + \frac{1}{2} \sum_{k=1}^{K-1} \sum_{m=1}^M \delta_{km} \ln \left(\frac{x_{ki}}{x_{Ki}} \right) \ln y_{mi} + v_i - u_i
 \end{aligned} \tag{11}$$

where α , β and δ are unknown parameters, v is a random error term, and $u_i = \ln D_i^I$ is the (non-negative) technical inefficiency term. The error term v is distributed as iid $N(0, \sigma^2)$, for u we assume a truncated normal distribution $N^+(m, \sigma^2)$ as suggested by Stevenson (1980).

In order to capture systematic differences in exogenous factors between firms, we also include environmental variables to allow variation of a company's mean efficiency, assuming environmental factors directly affecting technical efficiency. As suggested by Battese and Coelli (1995), we assume the mean of the truncated normal distributed inefficiency term to be a linear function of environmental variables z (here as country dummies or density factors). For our model, m is specified as:

$$m_i = \lambda_0 + \sum_{s=1}^S \lambda_s z_{si} \tag{12}$$

Following Battese and Coelli (1995), we estimate the coefficients α , β , δ and λ , the standard deviations of the error components σ_u and σ_v , the total error variance $\sigma^2 = \sigma_u^2 + \sigma_v^2$ and the ratio of the variance of the inefficiency component to the total

error variance $\gamma = \sigma_u^2 / \sigma^2$. γ is bounded between zero and unity and indicates the relative contribution of inefficiency to total error variance.

The technical efficiency scores are calculated following the procedure by Coelli et al. (1999). Technical efficiency for the i -th firm in a set of cross-sectional data is defined by:

$$TE_i = E[\exp(-u_i | \varepsilon_i)]$$

$$= \left\{ \exp \left[-\mu_i + \frac{1}{2} \sigma_*^2 \right] \right\} \left\{ \frac{\Phi \left[\frac{\mu_i - \sigma_*}{\sigma_*} \right]}{\Phi \left[\frac{\mu_i}{\sigma_*} \right]} \right\} \quad (13)$$

with

$$\mu_i = (1 - \gamma) \left[\delta_0 + \sum_{s=1}^S \delta_s z_{s,i} \right] - \gamma \varepsilon_i \quad (14)$$

and

$$\sigma_*^2 = \gamma(1 - \gamma)\sigma^2 \quad (15)$$

4. Modelling Approach and Estimation Strategy

We now turn to the modelling of the electricity distribution technology. First, we specify the relevant input and output variables for the stochastic frontier model. Second, we specify the functional form of the models to be estimated. Concerning the variables, previous research on efficiency measurement in electricity distribution has used a variety of variables and models (Jamasp and Pollitt, 2001). This may be explained partly by lack of data and partly by the nature of issues addressed (Hattori et al., 2005).

In order to estimate relative efficiency and optimal firm size when taking the quality dimension into account, we specify two basic models. The first model (Cost-Only) focuses on efficiency only and consists of one input variable and three output variables. A single cost input is used to represent *total expenditures* (TOTEX) or total cash cost in

1
2
3 monetary terms defined as the sum of operating expenditures (OPEX) and capital
4 expenditures (CAPEX). While OPEX represents operating and maintenance (O&M)
5 costs, CAPEX represents the annual gross capital outlays of a company. Using a single
6 monetary measure for inputs facilitates international comparison, as it reflects
7 differences in relative factor prices and substitution between OPEX and CAPEX among
8 the countries. The issues of differences in cost levels, accounting rules, currencies
9 conversion and other input level influencing factors will be discussed later.

10
11
12
13
14
15
16
17 The second model (Cost-Quality) incorporates quality of service by using the number of
18 *customer minutes lost* (CML) for each firm. CML represents the continuity dimension of
19 quality of service, it measures the average duration of outages per connected customer
20 and is a proxy for service reliability. Following Yaisawarng and Klein (1994) and
21 Giannakis et al. (2005), we treat outage duration as an undesirable input, assuming a
22 substitutive relationship between total spending and duration of outages. In an input
23 distance function model, an efficient firm can reduce CML and cost while maintaining a
24 given level of outputs.

25
26
27
28
29
30
31
32 Electricity distribution utilities operate in a regulated environment and provide a
33 required amount of energy to a given number of customers as a joint service. The two
34 elements of this service, electricity delivered and number of customers supplied, can be
35 treated separately, as they (i) drive different costs, and (ii) interact with each other
36 technically. Therefore, we use two output variables in the cost-only and the cost-quality
37 models. These variables have been identified based on the “separate marketability of
38 components” property suggested by Neuberger (1977), that is total *number of customers*
39 and *number of energy units supplied* measured in Gigawatt-hours (GWh). The two
40 output variables also reflect the structure of a two-part tariff, i.e. a fixed charge per
41 customer as well as a variable part dependent on consumed energy. In addition,
42 economies of scope between customers and supplied energy have been theoretically
43 identified based on advantages in load-management due to a lower risk of stochastic
44 demand effects (law of large numbers) and the possibility of pooling non-perfectly
45 correlated demands to flatten total demand (Brunekreeft, 2003). These effects gain
46 importance with increasing number of customers, relating economies of scope to

economies of scale. A separate analysis of number of customers and energy units delivered allows the identification of economies of scale and scope.

In addition to input and output variables, environmental factors can influence the technical efficiency of a firm but are beyond managerial control. We use *customer density* (number of customer per network kilometre) as an environmental variable to control for density advantages. A set of country dummy variables is used to capture national differences such as ownership structure, regulation (antitrust rules), different objectives for utilities as well as differences in historical developments regarding size of service area and regulation regime.

Since the translog functional form requires an approximation of an underlying function to a specific point of the sample, we correct the variables by sample means. This procedure reduces the influence of outliers without affecting the structure of data. In addition, the first order coefficients can be interpreted as estimates of production elasticities at sample means (Coelli et al., 2003).

For the cost-only model (Model I), the outputs are energy delivered and number of customers, and the single input is total expenditures (TOTEX). Inclusion of country dummies as environmental variables allows us to adjust estimates of relative efficiency for structural differences which might be attributed to the regulatory regime, historical industry structure and results of former regulation. Moreover, we control for the differences in customer density which is expected to have an effect on firm-specific technical efficiency.

$$\begin{aligned}
 -\ln(TOTEX_i) = & \\
 & \alpha_0 + \alpha_1 \ln energy + \alpha_2 \ln customers \\
 & + \frac{1}{2} \alpha_{11} \ln energy^2 + \frac{1}{2} \alpha_{22} \ln customers^2 \\
 & + \alpha_{12} \ln energy * \ln customers \\
 & + v_i - u_i
 \end{aligned} \tag{16}$$

and,

$$\mu_i = \lambda_0 + \lambda_{UK} + \lambda_{Fi} + \lambda_{Sw} + \lambda_{No} + \lambda_{It} + \lambda_{Neth} + \lambda_{cust_dens} \tag{17}$$

We now extend the discussion to a cost-quality model (Model II), which incorporates customer minutes lost as a second input.

$$\begin{aligned}
 -\ln(TOTEX_i) = & \\
 & \alpha_0 + \alpha_1 \ln energy + \alpha_2 \ln customers \\
 & + \frac{1}{2} \alpha_{11} \ln energy^2 + \frac{1}{2} \alpha_{22} \ln customers^2 \\
 & + \alpha_{12} \ln energy * \ln customers \\
 & + \beta_1 \ln\left(\frac{CML}{TOTEX}\right) + \frac{1}{2} \beta_{11} \ln\left(\frac{CML}{TOTEX}\right)^2 \\
 & + \delta_1 \ln\left(\frac{CML}{TOTEX}\right) * \ln energy + \delta_2 \ln\left(\frac{CML}{TOTEX}\right) * \ln customers \\
 & + v_i - u_i
 \end{aligned} \tag{18}$$

and,

$$\mu_i = \lambda_0 + \lambda_{UK} + \lambda_{Fi} + \lambda_{Sw} + \lambda_{No} + \lambda_{It} + \lambda_{Neth} + \lambda_{cust_dens} \tag{19}$$

Table 1 shows the inputs, outputs, and environmental variables used in our models.

Table 1:
Specification of models

Variable	Model I	Model II
Inputs		
TOTEX	√	√
CML		√
Outputs		
No. of customers	√	√
Units of energy (GWh)	√	√
Environmental Factors (z)		
Country dummies	√	√
Customer density	√	√

5. Data and Descriptive Information

The data set used for this study consists of 505 electricity distribution utilities from eight European countries, namely Finland, Ireland, Italy, the Netherlands, Norway, Spain, Sweden and the United Kingdom. The data was collected from national regulators and utility associations for the financial year 2002. This section describes in detail how the data was harmonized and processed.

Using monetary values of input variables from an international data set bears some problems, the most relevant being comparability. As stated in Edvardsen and Førsund (2003), the range of practical alternatives for harmonizing is small. We convert the financial data to a single monetary unit, the euro, as suggested in Jamasb and Pollitt (2003). Five of eight countries in the sample have euro as their common currency. As conventional exchange rates do not fully cover country specific differences in price level and purchasing power, we adjusted the OPEX and CAPEX with the comparative price levels for 2002 using purchasing power parities (OECD, 2004).¹⁰ Table 2 shows descriptive information of the data set, the variables and their average values. Table 3 describes the variables and summary statistics of data used.

¹⁰ Jamasb and Pollitt (2003) in a Data Envelopment Analysis of efficiency of electricity distribution networks (in Norway, UK, Netherlands, Italy, Spain, Portugal) found a correlation coefficient of 0.99 between the efficiency scores when using PPP vs. using exchange rates. Furthermore, 4 out of 7 countries share a common currency, bearing difficulties accounting for relative price level differences when using currency rates.

Table 2:
Number of utilities in the sample

Country	Number of utilities (mean)	Energy supplied (GWh) (mean)	No. of customers (mean)	Network length (km) (mean)	TOTEX (in 000) (mean)	CML (mean)
United Kingdom	14	22,249	1,953,809	54,669	218,733	86.36
Ireland	1	21,208	1,737,616	164,553	658,016	398.00
Netherlands	7	13,340	851,894	254,835	254,835	16.66
Finland	99	483	32,879	4,126	30,436	136.23
Norway	143	504	17,872	2,084	8,248	240.72
Sweden	223	398	20,576	1,807	6,495	34.62
Italy	8 Enel departments	26,626	3,658,791	129,505	176,766	142.26
Spain	4	50,689	5,784,686	154,707	2,256,987	0.14

Table 3:
Variables and summary statistics

Variable	Min	Max	Mean	Median
No. of customers (in 000)	0.004	10,262.00	197.38	10.34
Energy supplied (GWh)	0.290	85,080	2,128	220
Network length (km)	10	280,166	7,866	987
TOTEX (in 000)	79.14	3,812,540	43,668	4,224
CML	.00	4834.68	117.02	43.39

As shown in the Table 2, the number of companies and the mean parameter values per country varies widely. For the UK, Ireland, Finland, Norway, Sweden and Spain, our sample is a near complete inventory count of utilities. For the Netherlands, separate financial data was not available for 2002 and we aggregated the technical and quality variables at the holding company level. Data for Italy's Enel distribution region information was aggregated from 19 sub-departments to 8 departments. Despite the data aggregation in both Italy and the Netherlands, our data set covers nearly the whole of the national distribution networks. The large differences between the countries (Table 2)

and the minimum and maximum values of variables (Table 3) demands interpretation of results with care; on the other hand, it allows an unbiased identification of optimal firm size across a wider range.

Concerning our hypotheses, the descriptive statistics show interesting relationships between costs, firm size, and quality of service. The plot of total expenditures against number of customer shows a decreasing increase in costs (Figure 2). On a per customer basis, Figure 3 indicates a cost advantage for larger companies, supporting the economies of scale hypothesis.

Figure 2:

Total expenses and firm size

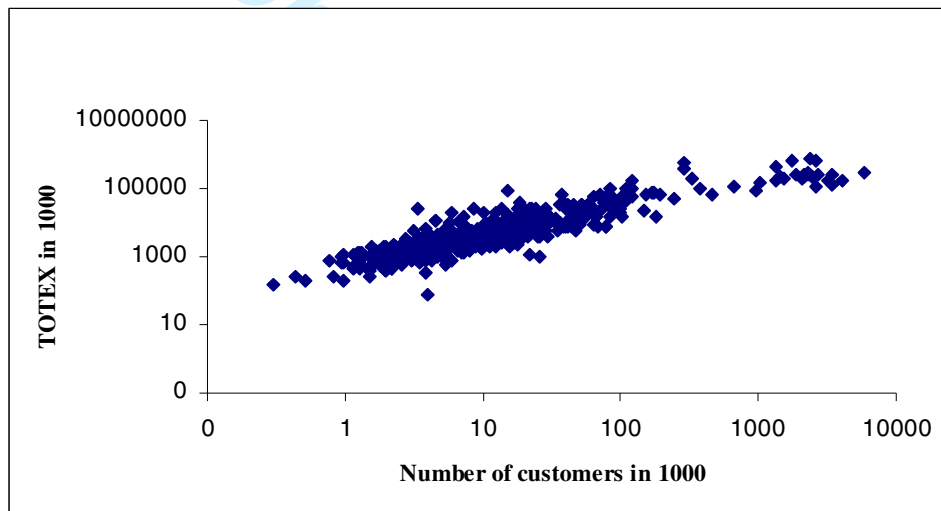


Figure 3:
Total expenses per customer and firm size

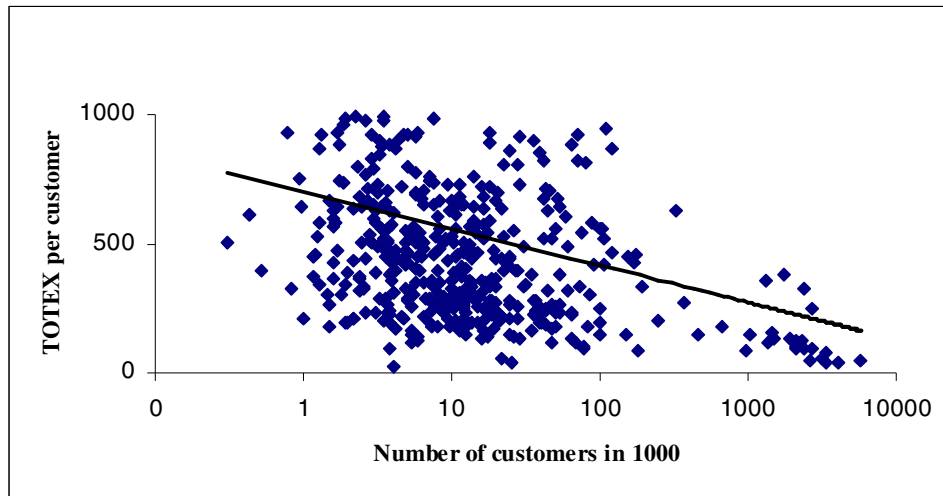


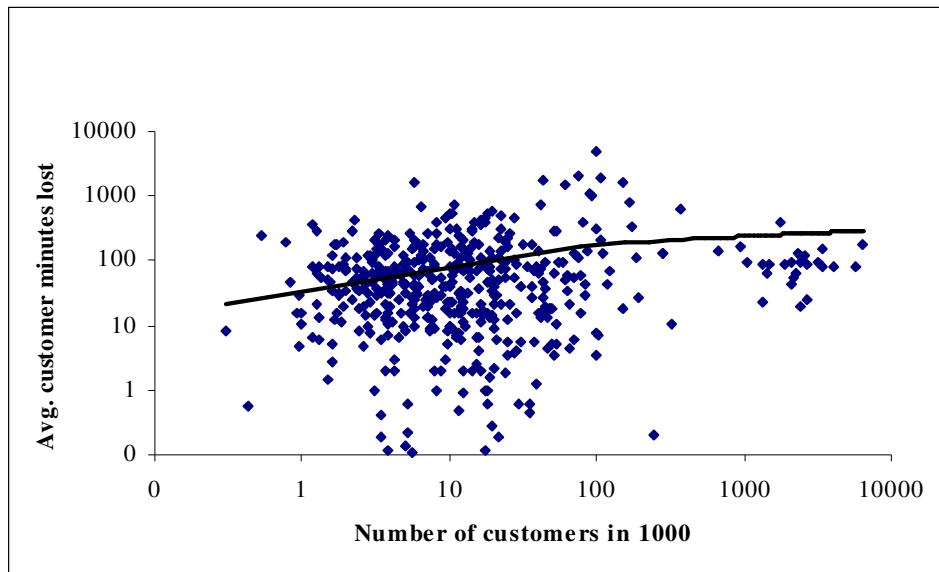
Figure 4 shows a scatter plot of the quality dimension (i.e. customer minute lost) against the number of customers as the relevant dimension of firm size. The figure shows that smaller firms exhibit a higher degree of service quality, supporting our proximity to customer hypothesis.

We controlled the data for outliers by applying the method suggested by Hadi (1992, 1994), which identifies multiple outliers in multivariate data. For the Model I, 15 observations were dropped and another 5 observations due to missing data. Data for Model II is adjusted for 34 outliers in total; after dropping 17 observations due to missing data, another 17 cases were eliminated based on Hadi's method.¹¹

¹¹ Applying the procedure suggested dropping all observations from Spain. To avoid systematic biases, we dropped the Spanish utilities for the cost-only model as well.

Figure 4:

Quality of service and firm size



6. Results

In this section we discuss the results of the estimated models, beginning with an analysis of technical efficiency and economies of scale for the cost-only Model I. We then extend the discussion to the quality incorporated model Model II.

Analysing the cost-only Model I (Table 4) the following conclusions can be drawn. The first order coefficients of $\ln energy$ and $\ln customer$ are statistically significant and show the expected signs. Also, the input TOTEX increases with both increasing energy delivered and number of customers. The country dummies and customer density influencing technical efficiency scores produce the following results. Five out of seven country variables are significant and can be interpreted as that the dummies for Nordic countries are all positive, indicating significant higher technical inefficiency for companies from Sweden, Norway or Finland. Customer density influences the technical efficiency score as expected, with increasing customer density, technical efficiency scores increase as well (to be exact, the negative sign represents a negative effect on

inefficiency).¹² The monotonicity restriction is not violated and the Wald χ^2 test confirms a systematic influence by explanatory variables at 99% level of significance.

Table 4:
Cost-Only Model I

In Energy	-0.4993*** [-2.79]	$\ln \sigma^2$	-1.037*** [-8.29]
In Customer	-0.4054** [-2.40]	$\text{inv log } \gamma$	0.004 [0.01]
$\frac{1}{2} (\ln \text{Energy})^2$	0.4092 [1.50]	σ^2	0.3546
$\frac{1}{2} (\ln \text{Customer})^2$	0.4194* [1.69]	γ	0.5011
In Energy * In Customer	-0.4138 [-1.61]	σ_v^2	0.1769
Constant	0.4383*** [3.72]	σ_u^2	0.1777
z UK	-0.212 [-0.19]	Log-likelihood	-403.5747
z Finland	1.613*** [8.45]	Wald χ^2	1476.23 [0.000]
z Sweden	0.544* [1.69]	N	485
z Norway	1.094*** [4.68]		
z Italy	-15.453 [-0.45]		
z Netherlands	1.193*** [2.92]		
z Customer / km	-10.547* [-1.83]		
Significant on 10%-, 5%-, and 1%-level: *, **, and ***; z value in parentheses.			

The relationship between technical efficiency and utility size in Model I indicates presence of considerable economies of scale: While the mean technical efficiency score is 0.45 for small utilities and 0.49 for medium sized utilities respectively, the larger

¹² We suppressed the environmental variables constant to obtain better interpretable results.

1
2
3 utilities show a mean score of nearly 0.80.¹³ This relation holds for the different
4 countries as well, while the UK (0.84) and Italy (0.82) show very efficient distribution
5 utilities, firms from Nordic countries tend to be rather inefficient. An interesting and not
6 expected result are the comparatively low efficiency scores for Ireland (0.54) and the
7 Netherlands (0.45). However, the confidence intervals of the efficiency scores are large
8 and to some extent overlap. This indeed coincides with other research and does not alter
9 the results in general.¹⁴

10
11
12 Also, returns to scale in relation to number of customers, economies of scale can be
13 found throughout the sample. The RTS measure remains constant at about 1.1, which is
14 the observed scale economies at the sample mean as well.¹⁵ Concerning the issue of
15 optimal firm size, these findings suggest that even the largest firms in the sample have
16 not exploited all scale economies; a further increase of the joint output vector seems
17 reasonable for the entire sample.

18
19
20 For the Model II with incorporated customer minutes lost as an additional input factor,
21 we estimated a two input two-output translog input distance function (Table 5). The first
22 order coefficients of *ln energy*, *ln customer*, and *ln cml* (normalized by TOTEX
23 variable) are highly significant and show the expected signs. While total expenditures
24 increase with energy delivered and number of customers, customer minutes lost
25 decrease with cost, indicating a trade-off relation between cost and quality. Again, five
26 out of seven environmental variables are significantly influencing firm's technical (in)
27 efficiency.¹⁶ The Nordic firms as well as those from the Netherlands are significantly
28 less efficient. The control variable for customer density shows a highly significant

29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
13 This analysis is based on the gross technical efficiency scores (see *Coelli, Perelman and Romano*
1999). Calculating net technical efficiency scores as suggested by Coelli et al. reduces the efficiency
differences between small and large firms but does not alter the relation in general.

14 To estimate the confidence intervals of the technical efficiency scores, we applied the procedure
suggested in *Horrace and Schmidt* (1996) and *Kumbhakar and Lovell* (2000). In *Kumbhakar and*
Lovell (2000), formula (3.2.34) contains a typo. We thank William C. Horrace for bringing this to
our attention. The interested reader may be referred to *Horrace and Schmidt* (2000).

15 Applying the procedure of testing for economies of joint production (*Denny and Pinto* 1978)
indicates that this result of constant scale economies throughout the sample cannot be explained by
scope economies. This seems to be counter-intuitive, as a comparable RTS measure for Model 2 can
clearly be described by increasing economies of scope with firm size (see below).

16 Again, we suppressed the environmental variables constant to obtain better interpretable results.

1
2
3 negative relation between number of customers per kilometre of network length and
4 technical inefficiency. As in Model I, the monotonicity restriction is not violated. The
5 Wald χ^2 test confirms a systematic influence by explanatory variables at 99% level of
6 significance.
7
8
9

10
11 The estimated efficiency scores clearly contradict the proximity to customer hypothesis.
12 While small firms show the lowest mean efficiency scores (0.38), technical efficiency
13 increases to 0.44 for medium sized and 0.81 for large firms.¹⁷ Again, this relationship
14 holds for the countries as well. Italy (0.99) and the UK (0.82) show rather high mean
15 efficiency scores while Finish (0.22) and Norwegian (0.30) utilities are inefficient on
16 average. An exception among the Nordic countries is Sweden with a mean quality
17 adjusted technical efficiency of the companies of 0.55. In cost-quality terms a
18 comparatively inefficient utility can be found in Ireland (0.37), Dutch firms show a
19 mean technical efficiency of 0.51. As in Model I, the confidence intervals of the
20 technical efficiency score are rather large and indicate coincidental differences in
21 technical efficiency to a certain extent.
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57

58
59
60
17 The net technical efficiency scores are less different between small and large firms; but again, this relation still holds in general.

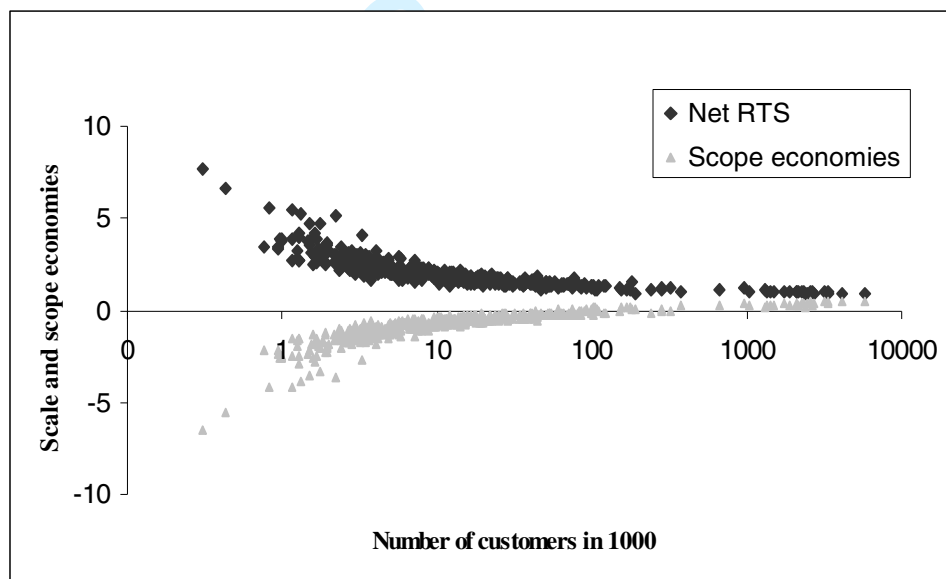
Table 5:
Cost-Quality Model II

In Energy	-0.3944** [-2.51]	$\ln \sigma^2$	-1.262*** [-13.84]
In Customer	-0.3440** [-2.43]	$\ln \gamma$	0.929** [2.20]
$\frac{1}{2} (\ln \text{Energy})^2$	-0.0483 [-0.18]	σ^2	0.2830
$\frac{1}{2} (\ln \text{Customer})^2$	0.2070 [0.90]	γ	0.7168
In Energy * In Customer	-0.0685 [-0.28]	σ_v^2	0.0801
In (CML/TOTEX)	0.2764*** [6.12]	σ_u^2	0.2028
$\frac{1}{2} (\ln \text{CML/TOTEX})^2$	0.0420*** [4.09]	Log-likelihood	-333.1597
In (CML/TOTEX) * In Energy	-0.1796*** [-3.24]	Wald χ^2	2561.28 [0.000]
In (CML/TOTEX) * In Customer	0.2169*** [3.93]	N	471
Constant	0.7067*** [6.79]		
z UK	0.068 [0.09]		
z Finland	1.847*** [12.43]		
z Sweden	0.809*** [4.39]		
z Norway	1.384*** [8.12]		
z Italy	-16.234 [-0.36]		
z Netherlands	1.227*** [3.34]		
Significant on 10%-, 5%-, and 1%-level: *, **, and ***; z value in parentheses.			

Analysing the returns to scale in relation to number of customers, economies of scale can be found throughout the sample with RTS at about 1.2 on average. Testing for economies of joint production (Denny and Pinto 1978) shows decreasing net returns to scale as well as increasing economies of scope with firm size. Net returns to scale are

homogenously decreasing throughout the sample, scale economies can be found for utilities below 183,000 customers (see Figure 5, dark squares).¹⁸ We calculated positive scope economies for utilities with more than 108,000 customers (Figure 5, light triangles).¹⁹ These findings support the assumed relation of energy supplied and number of customers: At a certain utility size, stochastic scale advantages or positive effects of pooling demand seem to develop. Our findings emphasize that the existence of scale related scope economies drive optimal firm size. Indeed, gross RTS scores above one for even the largest companies militate for an optimal utility size beyond the maximum observed number of customers in our sample. This result has to be treated with care as it is sensitive to the curvature of our estimated function. Nevertheless, for the given data set the results are viable.

Figure 5:
Net RTS, scope economies, and number of customers



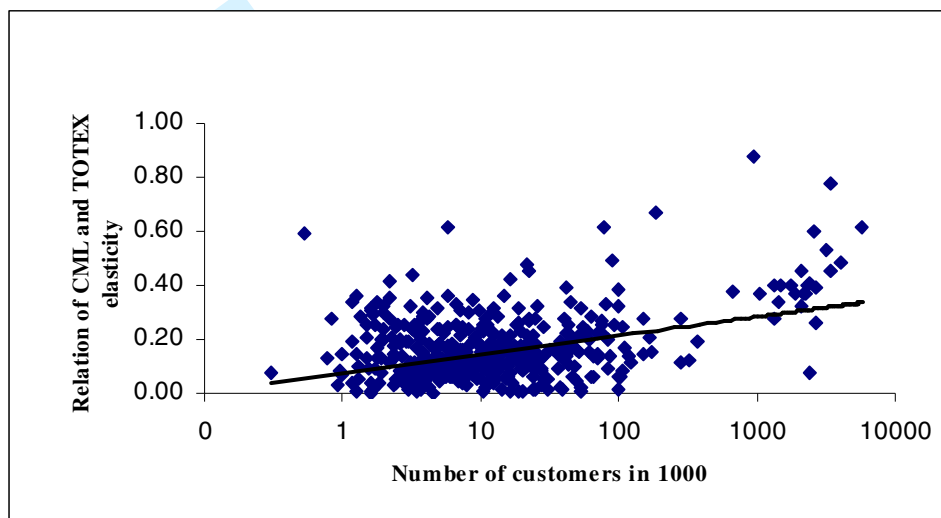
¹⁸ We obtained this result by estimating a logged trend function in a scatter plot diagram of returns to scale and number of customers, setting the trend equation to one and solving for the number of customers ($R^2 = 0.2317$).

¹⁹ This result was obtained by estimating a logged trend function in a scatter plot diagram of economies of scope and number of customers, setting the trend equation to one and solving for the number of customers ($R^2 = 0.2477$).

The relationship between the two inputs total expenditures and customer minutes lost, indicates that the ratio of the CML elasticity to the TOTEX elasticity increases with firm size (Figure 6). This measure of factor substitutability indicates that large utilities might be technically better able to increase quality of service at a given output level (by increasing total costs) while small utilities cannot substitute total expenses against quality to such an extent.

Figure 6:

Input substitution and firm size - Model II



Comparing and recapitulating the results from Models I and II, empirical evidence clearly supports the economies of scale hypothesis. In both the pure and the quality adjusted model, technical efficiency increases with firm size. Additionally, the efficiency differences are rather substantial. The efficiency differences in relation to firm size reflect the differences across countries as well. Countries with large utilities such as Italy and the UK show considerably higher mean technical efficiency scores than countries with smaller companies as the Nordic countries.

An interesting and somewhat unexpected result is that the proximity to the customer hypothesis can be rejected with confidence; empirical observations even give evidence to the contrary (Table 6). While incorporating quality of service increases average technical efficiency of large firms (and countries with predominantly large firms),

efficiency of small firms decreases substantially. Regressing the (logged) TE scores of Model II by those of Model I clearly support this finding; the TE scores are significantly negatively correlated, correlation is around 0.96.

Table 6:

Comparison of technical efficiency of Models I and II

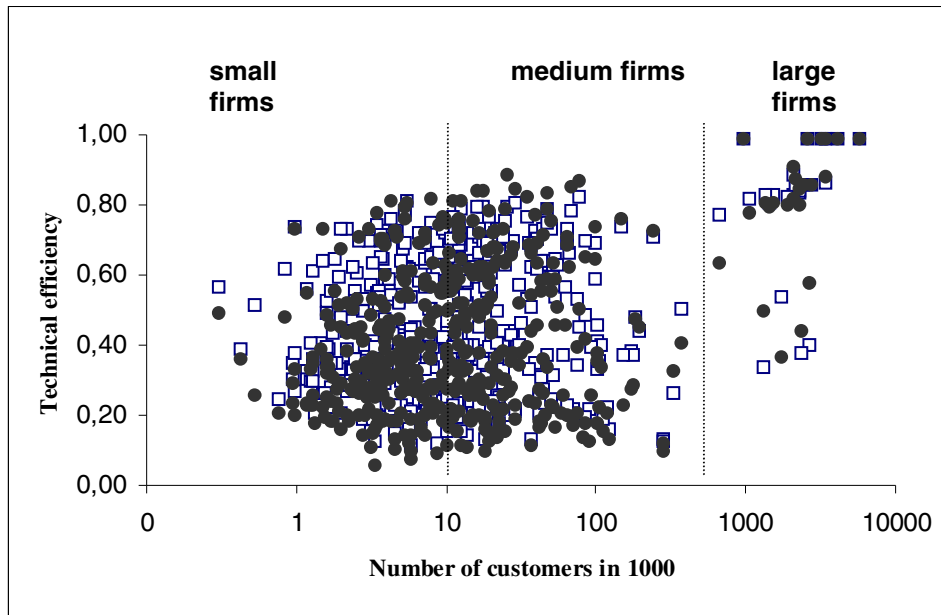
	Model	Mean	Std. Dev.	Min	Max	Average Change
Small firms*	Cost-only TE	0.4503	0.1722	0.1129	0.9255	-16.40%
	Cost-quality TE	0.3765	0.1768	0.0591	0.8193	
Medium firms*	Cost-only TE	0.4926	0.2004	0.1234	0.9885	-11.66%
	Cost-quality TE	0.4352	0.2176	0.0946	0.9868	
Large firms*	Cost-only TE	0.7963	0.1985	0.3380	0.9894	1.80%
	Cost-quality TE	0.8106	0.1788	0.3661	0.9891	
UK	Cost-only TE	0.8353	0.0274	0.7727	0.8854	-1.94%
	Cost-quality TE	0.8191	0.0658	0.6350	0.9106	
Finland	Cost-only TE	0.2507	0.1164	0.1129	0.7922	-11.39%
	Cost-quality TE	0.2222	0.1345	0.0738	0.8883	
Sweden	Cost-only TE	0.6189	0.1235	0.1281	0.9255	-10.76%
	Cost-quality TE	0.5523	0.1659	0.0591	0.8671	
Ireland	Cost-only TE	0.5381	0.0000	0.5381	0.5381	-31.96%
	Cost-quality TE	0.3661	0.0000	0.3661	0.3661	
Norway	Cost-only TE	0.3782	0.0549	0.2647	0.5516	-20.46%
	Cost-quality TE	0.3008	0.0676	0.1749	0.5472	
Italy	Cost-only TE	0.8169	0.0265	0.7720	0.8436	21.07%
	Cost-quality TE	0.9891	0.0003	0.9885	0.9894	
Netherlands	Cost-only TE	0.4445	0.1058	0.3380	0.5951	15.26%
	Cost-quality TE	0.5123	0.1143	0.3355	0.6477	
* Small firms are defined as being part of the 50% percentile of number of customers, medium firm are within the 50% to 95% percentile, large firms are the largest 5%.						

Figure 7 visualizes the differences in level and distribution of TE scores between Models I and II. The scatter plots of technical efficiency and number of customers show size advantages for both models; the distribution of the scores however is different. In Model I, the scores are less dispersed and the average technical efficiency is slightly higher. The scatter plot of Model II supports the results shown in Table 6. While small and especially less efficient firms seem to suffer from the inclusion of service quality

into the analysis, large and efficient firms seem to benefit in terms of efficiency scores. This result shows, illustrated in Figure 6, that large firms can supply quality at lower cost.

Figure 7:

Technical efficiency and firm size - Models I and II



7. Conclusions

Our analysis of the relationship between firm size, technical efficiency, and quality of service for European electricity distribution utilities shows evidence of significant economies of scale in electricity distribution networks. In addition, we found economies of scope between energy delivered and number of customers can be observed among larger firms.

Concerning quality of service and firm size, the results are ambiguous: our descriptive results indicate that small firms perform better in terms of quality of service. Since provision of quality is related to level of costs, this finding alone is not conclusive; the cost-quality models revealed that large utilities are technically more efficient even when

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

quality is controlled for, indicating that larger firms can supply a given level of quality of service at lower cost. Therefore, the hypothesis of customer proximity was rejected.

Regarding natural monopoly theory, the “proper” size of the natural monopoly utility does not appear to be affected when quality is incorporated in the analysis. Our analysis of the mean technical efficiency of utilities confirms the findings on firm size; we found significant differences among the countries and showed that smaller utilities and countries with smaller firms (i.e. Nordic utilities) tend to be significantly less efficient than large utilities from, for example, Italy or the UK. Additionally, the relationship between input elasticities (factor substitution) indicates that larger companies might, in contrast to small utilities, be able to increase quality more easily by increasing total expenses. These findings contradict previous studies on optimal utility size, such as Yatchew (2000) and Salvanes and Tjøtta (1994). While they found optimal size at a rather low scale; our analysis shows unexploited scale economies throughout the sample, indicating that utility size should be increased further even for large companies. These differences might be explained by basically three different factors. First, our analysis is based on a significantly larger sample with a broader range of firms. Second, in contrast to those previous studies, our sample includes a variety of comparably very large firms. And third, the positive scale economies throughout the sample can be explained by the relationship of firm size and economies of scope between number of customers and delivered energy, which has not been analysed in detail before.

The policy implications from our study are threefold. First, the possibility of factor substitution indicates the option of an increase in quality of service when appropriately regulated especially in countries with large utilities. This might diminish the current quality advantages of small utilities. Second, countries with a large number of small utilities should allow mergers in order to exploit potential gains. Third, in order to avoid collusion among utilities against regulatory agencies, we suggest a European harmonisation of data definition and collection and regulatory accounts to facilitate international comparisons and benchmarking.

Future research on technical efficiency, firm size and quality of service in network industries in general and electricity distribution in particular should address the issue of

1
2
3 productivity development over time. This would require panel data analysis to control
4 for cyclical effects and to overcome the shortcomings of cross-sectional analyses.
5 Another important aspect, not addressed in this study, is the relationship between
6 efficiency, quality, and ownership structure. Publicly owned utilities may, due to
7 differing managerial or corporate objectives, exhibit different performance in terms of
8 efficiency from private companies. Finally, the socio-economic costs of outages as well
9 as the cost of quality improvement need to be incorporated in the analysis in order to
10 improve incentive regulation schemes for quality of service.
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review

Acknowledgements

Left out for revision process

For Peer Review

References

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- Ai, C. and Sappington, D. E. M (1998) 'The Impact of State Incentive Regulation on the U.S. Telecommunications Industry', *University of Florida Discussion Paper*, University of Florida, Gainesville, FL.
- Aigner, D., Lovell, C. A. K., and Schmidt, P. (1977) 'Formulation and Estimation of Stochastic Frontier Production Function Models', *Journal of Econometrics*, 6, pp. 21-37.
- Ajodhia, V., Petrov, K., and Scarsi, G. C. (2004) 'Economic Benchmarking and its Applications', In: *Proceedings of the 3rd International Conference on Applied Infrastructures Research*, Oct. 9th (2004). Berlin, Germany.
- Atkinson, S. E. and Primont, D. (2002) 'Stochastic Estimation of Firm Technology, Inefficiency, and Productivity Growth Using Shadow Cost and Distance Functions', *Journal of Econometrics*, 108, pp. 203-225.
- Balk, B. M. (2001) 'Scale Efficiency and Productivity Change', *Journal of Productivity Analysis*, 15, pp. 159-183.
- Battese, G. and Coelli, T. (1995) 'A Model for Technical Inefficiency Effects in a Stochastic Frontier Production Function', *Empirical Economics*, 20, pp. 325-332.
- Baumol, W. J. (1977) 'On the Proper Cost Tests for Natural Monopoly in a Multiproduct Industry', *American Economic Review*, 67, pp. 809-822.
- Baumol, W. J., Panzar, J. C., and Willig, R. (1982), *Contestable Markets and the Theory of Industry Structure*. New York: Harcourt Brace Jovanovich
- Brunekreeft, G. (2003) *Regulation and Competition Policy in the Electricity Market: Economic analysis and German experience*. Baden-Baden: Nomos.
- CEPA (2003) *Background to Work on Assessing Efficiency for the 2005 Distribution Price Control Review, scope study – final report prepared for OFGEM*.
- Christensen, L. R., Jorgenson, D. W., and Lau, L. J. (1973) 'Transcendental Logarithmic Frontiers', *Review of Economics and Statistics*, 55, pp. 28-45.
- Codognet, M.-C., Glachant, J.-M., Leveque, F. and Plagnet, M-A. (2002), *Mergers and Acquisitions in the European Electricity Sector*, report prepared for the second edition of the international symposium on the M&As in the EU electricity sector (Ecole des Mines de Paris, September, 23, 2002)
- Coelli, T., Rao, P. D. S., and Battese, G. (1998) *An Introduction to Efficiency and Productivity Analysis*. New York: Kluwer Academic Publishers.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Coelli, T., Perelman, S., and Romano, E. (1999) 'Accounting for Environmental Influences in Stochastic Frontier Models: With Application to International Airlines', *Journal of Productivity Analysis*, 11, pp. 251-273.

Coelli, T., Estache, A., Perelman, S., and Trujillo, L. (2003) *A Primer on Efficiency Measurement for Utilities and Transport Regulators*. Washington: WBI Development Studies.

Denny, M. and Pinto, C. (1978) 'An Aggregate Model with Multi-Product Technologies', in: Melvyn, F. and McFadden, D. (eds.), *Production Economics: A Dual Approach to Theory and Applications*, Volume 2. Amsterdam: North Holland.

Dixit, A. (1997) 'Power of Incentives in Private vs. Public Organizations', *American Economic Review, Papers and Proceedings* 87 (2), pp. 378-382.

Edvardsen, D. F. and Førsum, F. R. (2003) 'International Benchmarking of Electricity Distribution Utilities', *Resource and Energy Economics*, 25, pp. 353-371.

Estache, A., Rossi, M., and Ruzzier, C. (2004) 'The Case for International Coordination of Electricity Regulation: Evidence from the Measurement of Efficiency in South America', *Journal of Regulatory Economics*, 25 (3), pp. 271-295.

Färe, R. and Primont, D. (1995) *Multi-Output Production and Duality: Theory and Applications*. New York: Kluwer Academic Publishers.

Filippini, M. (1996) 'Economies of Scale and Utilization in the Swiss Electric Power Distribution Industry', *Applied Economics*, 28, pp. 543-550.

Filippini, M. (1998) 'Are Municipal Electricity Distribution Utilities Natural Monopolies?', *Annals of Public and Cooperative Economics*, 69 (2), pp. 157-174.

Filippini, M. and Wild, J. (2001) Regional Differences in Electricity Distribution Costs and their Consequences for Yardstick Regulation of Access Prices, *Energy Economics*, 23 (4), pp. 477-488.

Giannakis, D., Jamasb, T., and Pollitt, M. (2005) 'Benchmarking and Incentive Regulation of Quality of Service: An Application to the UK Electricity Distribution Utilities', *Energy Policy*, 33 (17), pp. 2256-2271.

Giles, D. and Wyatt, N. S. (1993) 'Economies of Scale in the New Zealand Electricity Distribution Industry', in: Phillips, P. C. B. (ed.), *Models, Methods and Applications of Econometrics*. Oxford: Blackwell.

Gilsdorf, K. (1994) 'Vertical Integration Efficiencies and Electric Utilities: A Cost Complementarity Perspective', *Quarterly Review of Economics and Finance*, 34 (3), pp. 261-282.

Gilsdorf, K. (1995) 'Testing for Subadditivity of Vertically Integrated Electric Utilities', *Southern Economic Journal*, 62 (1), pp. 126-137.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Growitsch, C. and Wein, T. (2004) 'The Contestable Markets Theory: Efficient Advice for Economic Policy', in Hirschhausen, C., Beckers, T. and Mitusch, K. (eds.), *Trends in Infrastructure Regulation and Financing*, Chapter 3. Aldershot: Edward Elgar.

Hadi, A. S. (1992) 'Identifying Multiple Outliers in Multivariate Data', *Journal of the Royal Statistical Society, Series B*, 54, pp. 761-771.

Hadi, A. S. (1994) 'A Modification of a Method for the Detection of Outliers in Multivariate Samples', *Journal of the Royal Statistical Society, Series B*, 56, pp. 393-396.

Hattori, T., Jamasb, T., and Pollitt, M. (2005) 'Electricity Distribution in the UK and Japan: A Comparative Efficiency Analysis 1985-1998', *Energy Journal*, 26 (2), pp. 23-47.

Holmström, B., 1989, 'Agency Costs and Innovation', *Journal of Economic Behavior and Organisation*, 12 (3), pp. 305-327.

Horrace, W. C. and Schmidt, P. (1996) 'Confidence Statements for Efficiency Estimates from Stochastic Frontier Models', *Journal of Productivity Analysis*, 7, pp. 257-282.

Horrace, W. C. and Schmidt, P. (2000) 'Multiple Comparisons with the Best, with Economic Applications', *Journal of Applied Econometrics*, 15, pp. 1-26,

IPART (1999) 'Efficiency and Benchmarking Study of the NSW Distribution Businesses', Research Paper No. 13, Sydney. Prepared by London Economics for the Independent Pricing and Regulatory Tribunal, IPART. New South Wales.

Jamasb, T. and Pollitt, M. (2001) 'Benchmarking and Regulation: International Electricity Experience', *Utilities Policy*, 9 (3), pp. 107-130.

Jamasb, T. and Pollitt, M. (2003) 'International Benchmarking and Regulation: An Application to European Electricity Distribution Utilities', *Energy Policy*, 31, pp. 1609-1622.

Korhonen, P. and Syrjänen, M. (2003) 'Evaluation of Cost Efficiency in Finnish Electricity Distribution', *Annals of Operations Research*, 121 (1), pp. 105-122.

Kridel, D. J., Sappington, D. E. M., and Weisman, D.L. (1996) 'The Effects of Incentive Regulation in The Telecommunications Industry: A Survey', *Journal of Regulatory Economics*, 9 (3), pp. 269-306.

Kwoka, J. E. (2005), 'The Comparative Advantage of Public Ownership: Evidence from U.S. Electric Utilities', *Canadian Journal of Economics*, 38 (2), pp. 622-640.

Kumbhakar, S. C. and Lovell, C. A. K. (2000) *Stochastic Frontier Analysis* (Cambridge University Press, Cambridge).

1
2
3 Morrison Paul, C., Nehring, R., Banker, D., and Somwaru, A. (2004) 'Scale Economies
4 and Efficiency in U.S. Agriculture: Are Traditional Farms History?', *Journal of*
5 *Productivity Analysis*, 22, pp. 185-205.

6
7
8 Meeusen, W. and van den Broeck, J. (1977) 'Efficiency Estimation from Cobb-Douglas
9 Production Functions with Composed Error', *International Economic Review*, 18 (2),
10 pp. 435-444.

11
12 Nerlove, M. (1963) 'Returns to Scale in Electricity Supply', in: Christ, C.F. (ed.),
13 *Measurement in Economics*. Stanford: Stanford University Press.

14
15
16 Neuberg, L. (1977) 'Two Issues in Municipal Ownership of Electric Power Distribution
17 Systems', *Bell Journal of Economics*, 8 (Spring), pp. 303-323.

18
19
20 OECD (2004) *Main Economic Indicators*, Organisation for Economic Cooperation and
21 Development, Paris: mimeo.

22
23 Orea, L. (2002) 'Parametric Decomposition of a Generalized Malmquist Productivity
24 Index', *Journal of Productivity Analysis*, 18, pp. 5-22.

25
26
27 Pollitt, M. (1995) *Ownership and Performance in Electric Utilities*. Oxford: Oxford
28 University Press.

29
30 Ray, S. (1999) 'Measuring Scale Efficiency from a Translog Production Function',
31 *Journal of Productivity Analysis*, 11, pp. 183-195.

32
33
34 Ray, S. (2003) Measuring Scale Efficiency from the Translog Multi-Input, Multi-
35 Output Distance Function, Working Paper 2003-25, University of Connecticut. Storrs,
36 CT.

37
38 Resende, M. and Façanha, L. O. (2005) 'Price-Cap Regulation and Service-Quality in
39 Telecommunications: an Empirical Study', *Information Economics and Policy*, 17, pp.
40 1-12.

41
42
43 Rungsuriyawiboon, S. and O'Donnell, C., (2004) Curvature-Constrained Estimates of
44 Technical Efficiency and Returns to Scale for U.S. Electric Utilities, CEPA Working
45 Paper Series, No. 07/2004. University of Queensland, St. Lucia, Qld.

46
47
48 Salvanes, K. G. and Tjøtta, S. (1994) 'Productivity Differences in Multiple Output
49 Industries: An Empirical Application to Electricity Distribution', *Journal of*
50 *Productivity Analysis*, 5, pp. 23-43.

51
52
53 Salvanes, K. G. and Tjøtta, S. (1998) 'A Test for Natural Monopoly with Application to
54 Norwegian Electricity Distribution', *Review of Industrial Organization* 13, 669-685.

55
56
57 Sappington, D. E. M. (2002) Price Regulation and Incentives, in: Cave, M., Majumdar,
58 S. and Vogelsang, I. (eds.), *Handbook of Telecommunications Economics*. Amsterdam:
59 North-Holland.

1
2
3 Sharkey, W. H. (1982) *The Theory of Natural Monopoly*. Cambridge: Cambridge
4 University Press.
5

6
7 Shephard, R. W. (1953) *Cost and Production Functions*. Princeton: Princeton
8 University Press.
9

10
11 Shephard, R. W. (1970) *Theory of Cost and Production Functions*. Princeton: Princeton
12 University Press.
13

14
15 Stevenson, R. E. (1980) 'Likelihood Functions for Generalized Stochastic Frontier
16 Estimation', *Journal of Econometrics*, 13 (1), pp. 57-66.
17

18
19 Ter-Martirosyan, A. (2003) The Effects of Incentive Regulation on Quality of Service in
20 Electricity Markets, Department of Economics, George Washington University,
21 Working Paper, <http://www.ios.neu.edu/iioc2003/paper/termar.pdf>.
22

23
24 Whiteman, J. (1995) 'Benchmarking Developing Country Electricity Systems Using
25 Data Envelopment Analysis', *Asia-Pacific Economic Review*, 1 (3), pp. 71-78.
26

27
28 Wood, A. J. and Wollenberg, B. F. (1984) *Power Generation, Operation and Control*.
29 London: John Wiley & Sons.
30

31
32 Yaisawarng, S. and Klein, J. D. (1994) 'The Effects of Sulfur Dioxide Controls on
33 Productivity Change in the US Electric Power Industry', *The Review of Economics and
34 Statistics*, LXXVI (3), pp. 447-460.
35

36
37 Yatchew, A. (2000) 'Scale Economies in Electricity Distribution – A Semiparametric
38 Analysis', *Journal of Applied Econometrics*, 15, pp. 187-210.
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60