Appendices: Economic and Environmental Consequences of Market Power in the South-East Europe Regional Electricity Market

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Appendix A Calibration

The installed generation capacity by firm at each node is based on year-2013 data collected from firms' Websites such that the aggregate capacity per country matches data from ENTSO-E (2013) (Table A-1). Generation output is based on ENTSO-E (2013) and Eurostat (2014). Tables A-2–A-3 indicate transmission capacities (ENTSO-E, 2013; Terna, 2013). Time is represented by four representative hours for each month of 2013 (Table A-4). The load curve depends on the ratio of the block average load (over the number of hours in that block) and the monthly average load (over the number of hours in that month). Four load curves for selected months are given in Table A-5, which provide multipliers for the reference demand that add variation to the average demand through inverse-demand function coefficients, $D_{t,n}^{int}$ and $D_{t,n}^{slp}$. Finally, since the number of hours in each block, N_t, varies based on the month, Table A-6 shows the number of hours in each of the blocks of 28-, 30-, and 31-day months.

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Table A-1: Installed generation capacity mix per node (GW)

Node.Firm \ Technology	Gas	Coal	Oil	CCGT	Nuclear	Lignite	Mixed	Hydro
$n_1.i_1$	0.19			4.57				0.40
$n_1.i_2$				0.41				
$n_1.i_3$				2.51				0.46
$n_1.i_4$		0.84		2.25			1.15	1.45
$n_1.i_5$	0.06			3.27				
$n_1.i_6$				2.88				
$n_1.i_7$		0.33		1.18				
$n_1.i_8$	0.05			2.11				0.07
$n_1.i_9$		0.33		1.20				
$n_1.i_{23}$	0.05			0.62			1.90	2.31
$n_2.i_3$	0.26			0.23				0.02
$n_2.i_4$				0.76				0.06
$n_2.i_7$	0.36			0.39				
$n_2.i_{23}$	0.06		0.05	0.43			0.5	0.35
$n_3.i_1$				0.8				0.02
$n_3.i_2$				0.65				
$n_3.i_3$				0.13				
$n_3.i_4$		1.98						0.31
$n_3.i_7$	0.16			0.8				
$n_3.i_9$	0.16			1.6				
$n_3.i_{23}$	0.5		0.08	0.62			0.13	0.2
$n_4.i_1$				0.4				0.13
$n_4.i_2$				0.76				
$n_4.i_3$				2.0				
$n_4.i_4$		0.04						0.06
$n_4.i_6$				0.41				
$n_4.i_9$				1.57				
$n_4.i_{23}$	0.48			0.96				0.07
$n_5.i_4$		0.6						0.06
$n_5.i_6$		0.6						
$n_5.i_{23}$			0.42	0.58				
$n_6.i_1$			1.28					
$n_6.i_3$				0.15				
$n_6.i_4$	1.01		0.17	1.09				0.07
$n_6.i_6$	0.21							
$n_6.i_{23}$	0.1			0.41			0.11	
$n_7.i_1$		0.17	0.81					
$n_8.i_{23}$				0.4				
$n_9.i_1$		0.64						
$n_9.i_4$		2.64						
$n_9.i_5$				1.32				
$n_{11}.i_{23}$				0.48				
$n_{12}.i_{13}$					0.35			
$n_{12}.i_{14}$	0.08		0.06			0.79		0.41
$n_{12}.i_{15}$					0.35		0.30	0.10
$n_{12}.i_{23}$							0.08	
$n_{13}.i_{13}$	0.16	0.32	0.32	0.09			0.91	0.92
$n_{14}.i_{10}$						1.17		0.21
$n_{14}.i_{23}$						0.41		0.59
$n_{15}.i_{16}$	0.31					5.28		1.26
$n_{16}.i_1$		0.10						0.13
$n_{16}.i_{19}$		0.12						0.18
$n_{17}.i_{18}$	0.25		0.19			0.72		0.18
$n_{18}.i_3$				0.31				
$n_{18}.i_7$	0.07			0.22				
$n_{18}.i_{20}$	0.36		0.7	0.49		4.46	1.57	0.77
$n_{18}.i_{21}$				1.22				
$n_{18}.i_{23}$				0.67				
$n_{20}.i_3$				0.41				
$n_{20}.i_7$				1.09			0.31	
$n_{20}.i_{22}$	0.41			0.36	1.89		0.10	0.02
$n_{20}.i_{23}$		0.28	0.41	2.44			0.34	
$n_{21}.i_{11}$					2	1.85		0.53
$n_{21}.i_{12}$		1.26						
$n_{21}.i_{23}$		0.45		0.80		2.35		
$n_{22}.i_{17}$	1.58	2.50	0.67	0.44	1.3	4.23		1.70
$n_{22}.i_{23}$							0.07	

Table A-2: Transmission capacities for lines ℓ_1 to ℓ_{15} (GW)

Line	ℓ_1	ℓ_2	ℓ_3	ℓ_4	ℓ_5	ℓ_6	ℓ_7	ℓ_8	ℓ_9	ℓ_{10}	ℓ_{11}	ℓ_{12}	ℓ_{13}	ℓ_{14}	ℓ_{15}
Capacity	3.7	10	2.7	10	0.9	10	10	10	0.25	10	0.58	1	0.6	0.45	0.45

Table A-3: Transmission capacities for lines ℓ_{16} to ℓ_{31} (GW)

Line	ℓ_{16}	ℓ_{17}	ℓ_{18}	ℓ_{19}	ℓ_{20}	ℓ_{21}	ℓ_{22}	ℓ_{23}	ℓ_{24}	ℓ_{25}	ℓ_{26}	ℓ_{27}	ℓ_{28}	ℓ_{29}	ℓ_{30}	ℓ_{31}
Capacity	0.4	0.45	0.4	0.4	0.5	10	10	10	1.2	0.6	0.7	0.7	0.6	0.45	0.5	0.2

Table A-4: Intervals corresponding to four blocks

Block	Interval
Base load	min {load} - 70^{th} percentile {load}
Shoulder load	70^{th} percentile {load} - 95^{th} percentile {load}
Peak load	95^{th} percentile {load} - 99^{th} percentile {load}
Super-peak load	99^{th} percentile {load} - max{load}

Table A-5: Load curve for block per month

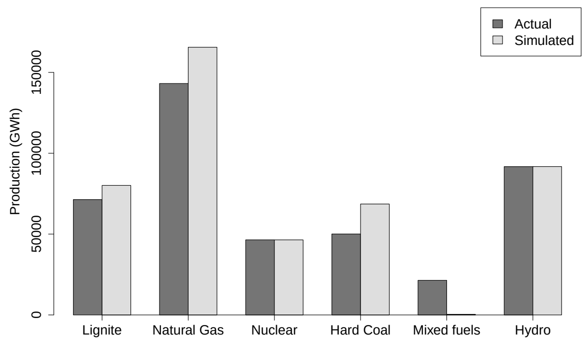
Month \ Block	Base load	Shoulder load	Peak load	Super-peak load
Jan	0.9	1.19	1.26	1.28
Feb	0.92	1.17	1.23	1.25
Jun	0.92	1.17	1.30	1.34
Dec	0.90	1.21	1.32	1.35

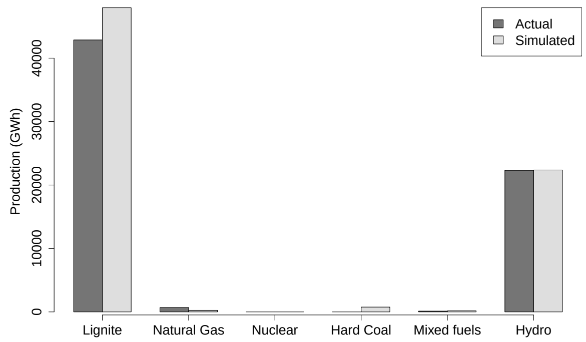
Table A-6: Number of hours per block

	Number of days in month		
Block	31	28	30
Base load	520	470	504
Shoulder load	186	168	180
Peak load	30	27	28
Super-peak load	8	7	8

For the purpose of calibration, we compare the simulated results under perfect competition at a permit price of €0/t with actual quantities from 2013. Generally, we are able to capture the main characteristics of the modelled system in terms of generation mix and emissions for ETS and non-ETS areas as well as electricity prices. In relation to the annual production in ETS (Figure A-1a), production from some fuel sources is overestimated (lignite, natural gas, and hard coal by 12.25%, 15.67%, and 37.05%, respectively), whereas there is hardly any production

Figure A-1: Annual production per technology in the ETS and non-ETS area of SEE-REM (Eurostat (2014) and ENTSO-E (2013))

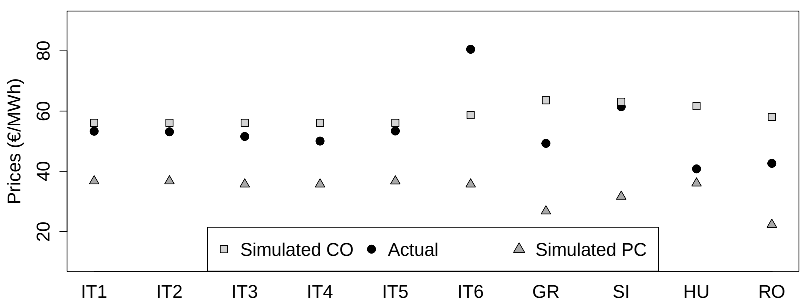




from mixed fuels and fuel oil (mixed fuels and fuel oil rarely seem to be viable options in our modelling framework). Overall production in ETS is overestimated by 6.76%. In the non-ETS area (Figure A-1b), we have an overproduction from lignite of 11.84% and overall overproduction of 8.33% compared to actual quantities. Consequently, production in the entire SEE-REM is overestimated by 6.98%. This overproduction could be explained by limitations of our model concerning technical constraints such as ramping and start-up costs.

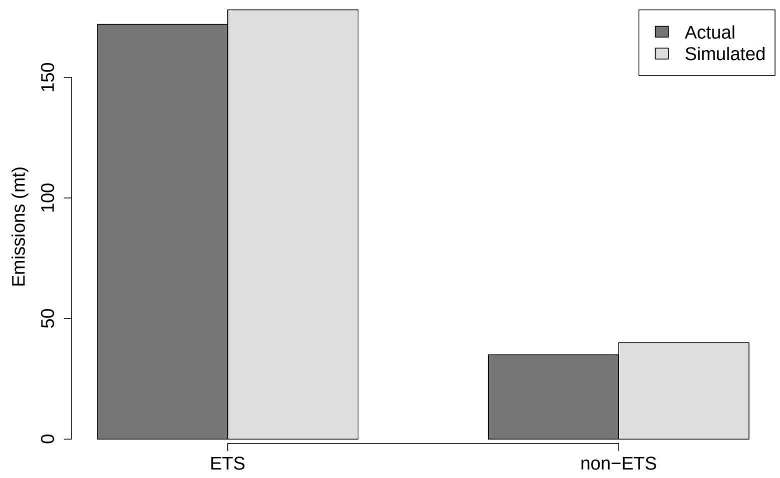
We calibrate average annual prices using the assumption of perfect competition and Cournot oligopoly (CO) where all actual firms considered in Section 3.3 are Cournot oligopolists (Figure A-2). As expected, the actual prices are bounded by the perfect competition setting and Cournot oligopoly setting apart from the price at node IT6. A possible explanation for this is a relatively large installed capacity of mixed fuels and fuel oil at node IT6 that could determine the actual price at that node; however, because our model almost never generates power from these sources, simulated prices remain relatively low.

Figure A-2: Average annual prices (Countries' power exchanges)



Under perfect competition, annual emissions for 2013 (Figure A-3) are overestimated in both ETS and non-ETS areas by 3.49% and 14.29%, respectively. Because the non-ETS area of SEE-REM is relatively small, overall SEE-REM emissions are overestimated by 5.31%, which we deem to be reasonable for the purpose of our analysis.

Figure A-3: Annual emissions in SEE-REM (Own calculation based on Eurostat (2014) and EU (2012))



Appendix B Additional Results

Table B-1: Production per fuel type (GWh) in Italy in PC-B10

Region \ Technology	Coal	Natural Gas	Other Fossil Fuels	Hydro	Total
North	12,215	102,304	31	44,793	159,343
of which Enel	*6,144*	*11,141*	*19*	*13,225*	*30,530*
of which fringe firms	*6,071*	*91,163*	*12*	*31,568*	*128,814*
South	39,014	35,549	-	6,913	81,476
of which Enel	*34,305*	-	-	*3,213*	*37,518*
of which fringe firms	*4,709*	*35,549*	-	*3,700*	*43,958*
Sardinia	8,830	2,648	10	486	11,974
of which Enel	*4,415*	-	-	*486*	*4,901*
of which fringe firms	*4,415*	*2,648*	*10*	-	*7,073*
Sicily	-	7,297	-	584	7,881
of which Enel	-	*5,141*	-	*584*	*5,725*
of which fringe firms	-	*2,156*	-	-	*2,156*
Total	60,059	147,798	41	52,776	260,674
of which Enel	*44,864*	*16,282*	*19*	*17,509*	*78,673*
of which fringe firms	*15,195*	*131,516*	*22*	*35,268*	*182,001*

Table B-2: Production per fuel type (GWh) in Italy in PC-B30

Region \ Technology	Coal	Natural Gas	Other Fossil Fuels	Hydro	Total
North	12,215	93,248	-	44,793	150,256
of which Enel	*6,144*	*10,178*	-	*13,225*	*29,547*
of which fringe firms	*6,071*	*83,071*	-	*31,568*	*120,709*
South	39,014	33,004	-	6,913	78,931
of which Enel	*34,305*	-	-	*3,213*	*37,518*
of which fringe firms	*4,709*	*33,004*	-	*3,700*	*41,413*
Sardinia	8,830	2,516	-	486	11,832
of which Enel	*4,415*	-	-	*486*	*4,901*
of which fringe firms	*4,415*	*2,516*	-	-	*6,931*
Sicily	-	6,910	-	584	7,494
of which Enel	-	*4,810*	-	*584*	*5,394*
of which fringe firms	-	*2,100*	-	-	*2,100*
Total	60,059	135,678	-	52,776	248,513
of which Enel	*44,864*	*14,988*	-	*17,509*	*77,360*
of which fringe firms	*15,195*	*120,690*	-	*35,268*	*171,152*

Table B-3: Change in production (GWh) from PC-B10 in Italy in S-T-B10

Region \ Technology	Coal	Natural Gas	Other Fossil Fuels	Hydro	Total
North	-	4,855	41	-	4,896
of which Enel	-	*2,334*	*- 19*	-	*2,315*
of which fringe firms	-	*2,521*	*60*	-	*2,581*
South	- 764	- 4,244	-	-	- 5,009
of which Enel	*- 764*	-	-	-	*- 764*
of which fringe firms	-	*- 4,244*	-	-	*- 4,244*
Sardinia	- 158	- 179	-	-	- 337
of which Enel	*- 158*	-	-	-	*- 158*
of which fringe firms	-	*- 179*	-	-	*- 179*
Sicily	-	- 258	-	-	- 258
of which Enel	-	*- 1,443*	-	-	*- 1,443*
of which fringe firms	-	*1,185*	-	-	*1,185*
Total	- 923	174	41	-	- 708
of which Enel	*- 923*	*891*	*- 19*	-	*- 51*
of which fringe firms	-	*- 717*	*60*	-	*- 657*

Table B-4: Change in production (GWh) from PC-B10 in Italy in S-B10

Region \ Technology	Coal	Natural Gas	Other Fossil Fuels	Hydro	Total
North	-1	-4,565	228	-	-4,338
of which Enel	*- 1*	*- 1,558*	*57*	-	*- 1,502*
of which fringe firms	-	*- 3,008*	*171*	-	*- 2,837*
South	-3,334	9,494	-	-	6,160
of which Enel	*- 3,334*	-	-	-	*- 3,334*
of which fringe firms	-	*9,494*	-	-	*9,494*
Sardinia	-223	-1,134	4	-	-1,353
of which Enel	*- 223*	-	-	-	*- 223*
of which fringe firms	-	*- 1,134*	*4*	-	*- 1,130*
Sicily	-	-1,034	-	-	-1,034
of which Enel	-	*- 751*	-	-	*- 751*
of which fringe firms	-	*- 284*	-	-	*- 284*
Total	-3,558	2,760	232	-	-566
of which Enel	*- 3,558*	*- 2,308*	*57*	-	*- 5,809*
of which fringe firms	-	*5,068*	*175*	-	*5,243*

Table B-5: Change in production (GWh) from PC-B30 in Italy in S-T-B30

Region \ Technology	Coal	Natural Gas	Other Fossil Fuels	Hydro	Total
North	- 139	- 3,798	-	- 4	- 3,940
of which Enel	*- 139*	*6,799*	-	*- 4*	*6,656*
of which fringe firms	-	*- 10,597*	-	-	*- 10,597*
South	- 2,825	11,102	-	- 3	8,275
of which Enel	*- 2,825*	-	-	*- 3*	*- 2,827*
of which fringe firms	-	*11,102*	-	-	*11,102*
Sardinia	- 524	294	-	-	- 230
of which Enel	*- 524*	-	-	-	*- 524*
of which fringe firms	-	*294*	-	-	*294*
Sicily	-	- 1,675	-	- 1	- 1,676
of which Enel	-	*- 611*	-	*- 1*	*- 612*
of which fringe firms	-	*- 1,064*	-	-	*- 1,064*
Total	- 3,487	5,924	-	- 8	2,429
of which Enel	*- 3,487*	*6,188*	-	*- 8*	*2,693*
of which fringe firms	-	*- 264*	-	-	*- 264*

Table B-6: Change in production (GWh) from PC-B30 in Italy in S-B30

Region \ Technology	Coal	Natural Gas	Other Fossil Fuels	Hydro	Total
North	-97	-3,913	-	-	-4,009
of which Enel	*- 97*	*4,222*	-	-	*4,125*
of which fringe firms	-	*- 8,134*	-	-	*- 8,134*
South	-2,559	3,981	-	-	1,422
of which Enel	*- 2,559*	-	-	-	*- 2,559*
of which fringe firms	-	*3,981*	-	-	*3,981*
Sardinia	-468	-568	-	-1	-1,037
of which Enel	*- 468*	-	-	*- 1*	*- 470*
of which fringe firms	-	*- 568*	-	-	*- 568*
Sicily	-	-964	-	-	-964
of which Enel	-	*- 1,524*	-	-	*- 1,524*
of which fringe firms	-	*560*	-	-	*560*
Total	-3,124	-1,464	-	-1	-4,589
of which Enel	*- 3,124*	*2,698*	-	*- 1*	*- 427*
of which fringe firms	-	*- 4,162*	-	-	*- 4,162*

Table B-7: Production per fuel type (GWh) in SEE-REM in B0 and B10

Scenario \ Technology	Coal	Natural Gas	Lignite	Other Fossil Fuels	Nuclear	Hydro	Total
PC-B0							
ETS excl. Italy	*8,560*	*11,909*	*80,108*	*146*	*46,421*	*38,991*	*186,136*
ETS	68,619	165,577	80,108	395	46,421	91,768	452,888
Non-ETS	759	251	47,947	173	-	22,369	71,499
Total	69,378	165,828	128,056	568	46,421	114,136	524,387
S-B0 (change from PC-B0)							
ETS excl. Italy	*- 110*	*- 395*	*- 28*	*- 12*	-	-	*- 546*
ETS	- 1,029	- 957	- 28	176	-	- 1	- 1,839
Non-ETS	- 1	- 15	116	- 2	-	-	98
Total	- 1,031	- 972	88	174	-	- 1	- 1,741
PC-B10							
ETS excl. Italy	*6,307*	*11,201*	*63,826*	*50*	*46,421*	*38,991*	*166,796*
ETS	66,366	158,999	63,826	91	46,421	91,768	427,470
Non-ETS	1,604	237	55,552	126	-	22,369	79,888
Total	67,970	159,236	119,378	218	46,421	114,136	507,358
S-T-B10 (change from PC-B10)							
ETS excl. Italy	*- 109*	*- 322*	*- 734*	*- 10*	-	-	*- 1,175*
ETS	- 1,032	- 148	- 734	30	-	-	- 1,883
Non-ETS	- 45	- 7	540	19	-	-	508
Total	- 1,077	- 154	- 194	49	-	-	- 1,376
S-B10 (change from PC-B10)							
ETS excl. Italy	*4,050*	*619*	*- 3,262*	*- 1*	-	-	*1,405*
ETS	492	3,379	- 3,262	231	-	-	839
Non-ETS	0	60	512	- 45	-	-	526
Total	492	3,439	- 2,751	185	-	-	1,365

Table B-8: Production per fuel type (GWh) in SEE-REM in B20

Scenario \ Technology	Coal	Natural Gas	Lignite	Other Fossil Fuels	Nuclear	Hydro	Total
PC-B20							
ETS excl. Italy	*19,938*	*11,369*	*33,324*	*3*	*46,421*	*38,991*	*150,048*
ETS	79,998	151,618	33,324	3	46,421	91,768	403,132
Non-ETS	1,604	229	56,371	53	-	22,369	80,625
Total	81,602	151,847	89,695	56	46,421	114,136	483,757
S-T-B20 (change from PC-B20)							
ETS excl. Italy	*84*	*- 423*	*- 169*	*- 1*	-	-	*- 509*
ETS	- 1,116	- 87	- 169	- 1	-	- 1	- 1,374
Non-ETS	-	- 2	-	21	-	-	20
Total	- 1,116	- 89	- 169	20	-	- 1	- 1,355
S-B20 (change from PC-B20)							
ETS excl. Italy	*1,396*	*509*	*- 323*	-	-	-	*1,582*
ETS	- 2,538	3,691	- 323	27	-	-	857
Non-ETS	-	18	3	22	-	-	42
Total	- 2,538	3,709	- 320	48	-	-	900

Table B-9: Production per fuel type (GWh) in SEE-REM in B30

Scenario \ Technology	Coal	Natural Gas	Lignite	Other Fossil Fuels	Nuclear	Hydro	Total
PC-B30							
ETS excl. Italy	*14,716*	*15,861*	*16,561*	-	*46,421*	*38,991*	*132,550*
ETS	74,775	151,539	16,561	-	46,421	91,768	381,063
Non-ETS	1,604	346	56,211	31	-	22,369	80,561
Total	76,379	151,885	72,772	31	46,421	114,136	461,624
S-T-B30 (change from PC-B30)							
ETS excl. Italy	*- 171*	*5,737*	*- 10,442*	-	-	-	*- 4,876*
ETS	- 3,658	11,661	- 10,442	-	-	- 8	- 2,448
Non-ETS	-	64	4	69	-	-	137
Total	- 3,658	11,725	- 10,438	69	-	- 8	- 2,310
S-B30 (change from PC-B30)							
ETS excl. Italy	*121*	*- 765*	*2,845*	-	-	-	*2,202*
ETS	- 3,002	- 2,228	2,845	-	-	- 1	- 2,387
Non-ETS	-	49	4	41	-	-	95
Total	- 3,002	- 2,179	2,850	41	-	- 1	- 2,291

Table B-10: Production per fuel type (GWh) in SEE-REM in B40

Scenario \ Technology	Coal	Natural Gas	Lignite	Other Fossil Fuels	Nuclear	Hydro	Total
PC-B40							
ETS excl. Italy	*7,432*	*27,111*	*3,732*	-	*46,421*	*38,991*	*123,687*
ETS	50,906	180,802	3,732	-	46,421	91,768	373,629
Non-ETS	1,604	1,399	56,176	137	-	22,369	81,685
Total	52,510	182,201	59,908	137	46,421	114,136	455,313
S-T-B40 (change from PC-B40)							
ETS excl. Italy	*2,611*	*- 2,721*	*276*	-	-	-	*165*
ETS	12,069	- 15,239	276	-	-	-	- 2,895
Non-ETS	-	14	-	-	-	-	14
Total	12,069	- 15,225	276	-	-	-	- 2,880
S-B40 (change from PC-B40)							
ETS excl. Italy	*185*	*974*	*239*	-	-	-	*1,397*
ETS	399	- 3,001	239	-	-	- 5	- 2,369
Non-ETS	-	-	-	-	-	-	-
Total	399	- 3,001	239	-	-	- 5	- 2,369

Table B-11: Consumption (GWh), net imports/exports (GWh), and emissions (kt) change from the respective PC scenario in Italy in perfect competition

Region \ Scenario	S-B0	S-T-B10	S-T-B20	S-T-B30	S-T-B40	S-B10	S-B20	S-B30	S-B40
Consumption									
North	- 1,128	- 911	- 803	- 1,244	- 1,517	- 377	- 312	- 1,231	- 1,294
South	- 284	- 251	- 195	- 550	- 743	- 518	- 336	- 577	- 521
Sardinia	- 71	- 96	- 149	- 268	- 305	- 32	- 173	- 208	- 268
Sicily	- 75	- 49	- 38	- 68	- 91	- 66	- 44	- 71	- 64
Total	- 1,557	- 1,308	- 1,185	- 2,129	- 2,655	- 993	- 864	- 2,087	- 2,147
Imports/Exports									
North	- 8,795	- 5,807	- 10,308	2,697	- 4,770	3,961	376	2,778	7,672
South	8,006	4,757	7,936	- 8,825	4,737	- 6,678	- 2,557	- 1,999	- 7,091
Sardinia	- 3	241	1,640	- 38	-521	1,321	1,603	830	1,833
Sicily	529	209	412	1,608	958	968	439	893	- 796
Total	- 264	- 600	- 319	- 4,558	405	- 427	- 139	2,502	1,619
Emissions									
North	2,875	1,797	3,451	- 1,478	2,298	- 1,450	- 318	- 1,489	- 3,640
South	- 3,335	- 2,110	- 3,295	1,923	136	959	- 419	- 462	3,417
Sardinia	- 45	- 183	- 765	- 284	459	- 574	- 838	- 555	- 1,325
Sicily	- 219	- 93	- 163	- 608	- 381	- 375	- 175	- 350	266
Total	- 724	- 590	- 772	- 447	2,512	- 1,440	- 1,750	- 2,856	- 1,282

Table B-12: Consumption (GWh), net imports/exports (GWh), and emissions (kt) in SEE-REM in perfect competition

Region \ Scenario	PC-B0	PC-B10	PC-B20	PC-B30	PC-B40
Consumption					
Italy	274,171	268,281	260,868	253,322	250,631
ETS excl. Italy	185,986	176,626	163,722	151,977	149,051
ETS	460,157	444,906	424,590	405,299	399,682
Non-ETS	64,230	62,452	59,167	56,325	55,631
Total	524,387	507,358	483,757	461,624	455,313
Import/Export					
Italy	7,419	7,607	7,783	4,808	690
ETS excl. Italy	-150	9,829	13,674	19,427	25,364
ETS	7,269	17,436	21,458	24,236	26,054
Non-ETS	-7,269	- 17,436	- 21,458	- 24,236	- 26,054
Emissions					
Italy	100,814	98,500	95,722	94,057	88,223
ETS excl. Italy	77,005	61,537	46,533	30,416	18,469
ETS	177,819	160,037	142,255	124,473	106,692
Non-ETS	40,441	47,303	47,907	47,806	48,334
Total	218,260	207,340	190,163	172,280	155,026

Table B-13: SEE-REM consumption (GWh), net imports/exports (GWh), and emissions (kt) change in Stackelberg scenarios from the respective perfect competition scenarios

Region \ Scenario	S-B0	S-T-B10	S-T-B20	S-T-B30	S-T-B40	S-B10	S-B20	S-B30	S-B40
Consumption									
Italy	- 1,557	- 1,308	- 1,185	- 2,129	- 2,655	- 993	- 864	- 2,087	- 2,147
ETS excl. Italy	- 186	- 63	- 157	- 156	- 187	2,185	1,835	- 145	- 165
ETS	- 1,743	- 1,370	- 1,341	- 2,286	- 2,843	1,192	971	- 2,232	- 2,313
Non-ETS	1	- 6	- 13	- 25	- 38	173	- 72	- 59	- 56
Total	- 1,741	- 1,376	- 1,355	- 2,310	- 2,880	1,365	899	- 2,291	- 2,369
Import/Export									
Italy	- 264	- 600	- 319	- 4,558	405	- 427	- 139	2,502	1,619
ETS excl. Italy	360	1,113	352	4,720	- 353	780	253	- 2,347	- 1,563
ETS	96	513	33	162	52	353	114	155	56
Non-ETS	- 96	- 513	- 33	- 162	- 52	- 353	- 114	- 155	- 56
Emissions									
Italy	- 724	- 590	- 772	- 447	2,512	- 1,440	- 1,750	- 2,856	- 1,282
ETS excl. Italy	- 265	- 814	- 231	- 6,670	1,188	550	959	2,164	689
ETS	- 989	- 1,404	- 1,003	- 7,117	3,700	- 890	- 791	- 692	- 593
Non-ETS	86	428	19	96	6	406	30	64	0
Total	-902	-976	-984	-7,021	3,706	-484	-761	-628	-593

Table B-14: Social welfare decomposition (k€)

Metric \ Scenario	PC-B0	PC-B10	PB-B20	PC-B30	PC-B40
Consumer Surplus	34,060,674.71	32,162,419.90	29,740,503.33	27,513,602.39	26,827,551.91
Producer Surplus	6,057,451.93	6,531,211.25	7,291,906.66	7,942,116.07	8,143,983.74
Merchandising Surplus	337,281.15	320,509.63	273,508.40	266,945.76	281,362.59
C&T Permit Revenue	-	1,382,226.23	2,848,368.29	3,951,966.29	3,816,382.50
Social Welfare	40,455,407.79	40,396,367.01	40,154,286.68	39,674,630.51	39,069,280.74
Change from PC	-	S-T-B10	S-T-B20	S-T-B30	S-T-B40
Consumer Surplus	-	- 201,450.25	- 224,431.43	- 371,669.51	- 440,007.55
Producer Surplus	-	174,878.54	188,044.29	331,664.23	414,761.45
Merchandising Surplus	-	8,226.29	17,667.18	16,179.93	6,891.34
C&T Permit Revenue	-	- 11,630.40	- 20,502.78	- 225,893.08	132,319.18
Social Welfare	-	- 29,975.82	- 39,222.74	- 249,718.43	113,964.42
Change from PC	S-B0	S-B10	S-B20	S-B30	S-B40
Consumer Surplus	- 248,029.42	73,012.37	- 23,632.63	- 367,983.29	- 374,590.70
Producer Surplus	216,198.99	221,847.30	300,403.90	336,639.89	343,381.27
Merchandising Surplus	8,058.52	- 24,285.63	- 9,648.18	8,547.39	13,459.91
C&T Permit Revenue	-	- 340,487.94	- 328,634.78	- 21,967.33	- 21,219.23
Social Welfare	- 23,771.91	- 69,913.90	- 61,511.69	- 44,763.34	- 38,968.75

Appendix C Nomenclature and Mathematical Reformulation

C.1 Nomenclature

Indices and Sets:

Γ	Upper-level decision variables
Ξ	Lower-level primal decision variables
Ψ	Lower-level dual variables
$i \in \mathcal{I}$	Firms
$j \in \mathcal{I}^F$	Follower firms price-takers $\mathcal{I}^F \subseteq \mathcal{I}$
$s \in \mathcal{I}^S$	Strategic producer index, $\mathcal{I}^S \cap \mathcal{I}^F = \emptyset$, $\mathcal{I}^S \cup \mathcal{I}^F = \mathcal{I}$
$u \in \mathcal{U}_{n,i}$	Generating units of firm i located at node n
$\ell \in \mathcal{L}$	Lines
$\ell^{AC} \in \mathcal{L}^{AC}$	AC lines, $\mathcal{L}^{AC} \subseteq \mathcal{L}$
$n \in \mathcal{N}$	Nodes
$n^{AC} \in \mathcal{N}^{AC}$	Nodes part of the AC network, $\mathcal{N}^{AC} \subseteq \mathcal{N}$
$n^{DC} \in \mathcal{N}^{DC}$	Nodes part of the DC network, $\mathcal{N}^{DC} \cup \mathcal{N}^{AC} = \mathcal{N}$
$n \in \mathcal{N}^{ETS}$	Nodes in the ETS area, $\mathcal{N}^{ETS} \in \mathcal{N}$
$t \in \mathcal{T}$	Time blocks

Parameters:

$A_{\ell,n}$	Network incidence matrix, 1 indicates a node where the line starts and -1 a node where the line finishes (-)
$C_{n,i,u}$	Marginal cost of production of generation unit u owned by firm i at node n (€/MWh)
$D^{int}_{t,n}$	Inverse-demand intercept at node n in time block t (€/MWh)
$D^{slp}_{t,n}$	Inverse-demand slope at node n in time block t (€/MW^{2}h)
$E_{n,i,u}$	Carbon intensity of production of generating unit u owned by firm i at node n (t/MWh)
$H_{\ell^{AC},n^{AC}}$	Network transfer admittance matrix for nodes $n^{AC} \in \mathcal{N}^{AC}$ and lines $\ell^{AC} \in \mathcal{L}^{AC}$ (S)
$K_{t,\ell}$	Capacity of line ℓ in time block t (MW)
N_t	Number of hours in time block t (h)
R	Carbon tax (€/t)
$S_{n^{AC}}$	Indicates the swing bus, 1 if swing, 0 otherwise at node $n^{AC} \in \mathcal{N}^{AC}$ (-)
$X_{n,i,u}$	Maximum production capacity of generation unit u owned by firm i at node n (MW)
Z	Carbon cap (t)
$M, \overline{M}, \widetilde{M}, \hat{M}, \check{M}, \underline{M}$	Large constants used in disjunctive constraints

Primal Variables:

$d_{t,n}$	Demand at node n in time block t (MW)
$f_{t,\ell}$	Flow on line ℓ in time block t (MW)
$v_{t,n^{AC}}$	Voltage angle at node $n^{AC} \in \mathcal{N}^{AC}$ in time block t (rad)
$x_{t,n,i,u}$	Quantity produced by generating unit u owned by firm i at node n in time block t (MW)

Dual Variables:

$\beta_{t,n,i,u}$	Maximum generation capacity constraint of generating unit u owned by firm i at node n in time block t (€/MWh)
$\gamma_{t,\ell^{AC}}$	Definition of AC flow on line $\ell^{AC} \in \mathcal{L}^{AC}$ in time block t (€/MWh)
δ_t	Hub price in time block t (€/MWh)
$\eta_{t,n^{AC}}$	Swing bus constraint at node $n^{AC} \in \mathcal{N}^{AC}$ in time block t (-)

$\lambda_{t,n}$	Energy mass-balance constraint at node n in time block t (€/MWh)
$\mu^-_{t,\ell}$	Maximum capacity constraint in negative direction on line ℓ in time block t (€/MWh)
$\mu^+_{t,\ell}$	Maximum capacity constraint in positive direction on line ℓ in time block t (€/MWh)
ρ	Price of CO_2 allowances (€/t)

Binary Variables:

$r_{t,n}$	Auxiliary variable used to handle the KKT condition with respect to demand at node n in time period t and $d_{t,n}$
$\overline{r}_{t,n,j,u}$	Auxiliary variable used to handle the KKT condition with respect to non-strategic producer j's generation from unit u located at node n in time period t and $x_{t,n,j,u}$
$\tilde{r}_{t,n,j,u}$	Auxiliary variable used to handle complementarity condition between generation constraint of non-strategic producer j's unit u located at node n in time period t and the shadow price of generation capacity $\beta_{t,n,j,u}$
$\hat{r}_{t,\ell}$	Auxiliary variable used to handle complementarity condition between transmission line ℓ's capacity constraint in time period t and shadow price in positive direction $\mu^+_{t,\ell}$
$\check{r}_{t,\ell}$	Auxiliary variable used to handle complementarity condition between transmission line ℓ's capacity constraint in time period t and the shadow price in negative direction $\mu^-_{t,\ell}$
$\underline{r}$	Auxiliary variable used to handle complementarity condition between the emissions constraint and price of CO_2 allowances ρ

C.2 KKT Conditions for the Lower Level

$$0 \le x_{t,n,j,u} \perp N_t\left(-\lambda_{t,n} + C_{n,j,u} + \rho E_{n,j,u} + \beta_{t,n,j,u}\right) \ge 0,\ \forall t, j, u \in \mathcal{U}_{n,j}, n \in \mathcal{N}^{ETS} \tag{C-1a}$$

$$0 \le x_{t,n,j,u} \perp N_t\left(-\lambda_{t,n} + C_{n,j,u} + \beta_{t,n,j,u}\right) \ge 0,\ \forall t, j, u \in \mathcal{U}_{n,j}, n \in \mathcal{N} \setminus \mathcal{N}^{ETS} \tag{C-1b}$$

$$0 \le d_{t,n} \perp N_t\Big(-D^{int}_{t,n} + D^{slp}_{t,n} d_{t,n} + \lambda_{t,n}\Big) \ge 0,\ \forall t, n \tag{C-2}$$

$$N_t\left(\sum_{n^{AC}\in\mathcal{N}^{AC}} (\delta_t - \lambda_{t,n^{AC}}) A_{\ell^{AC},n^{AC}} - \gamma_{t,\ell^{AC}} + \mu^-_{t,\ell^{AC}} - \mu^+_{t,\ell^{AC}}\right) = 0,\ f_{t,\ell^{AC}} \text{ free},\ \forall t, \ell^{AC} \in \mathcal{L}^{AC} \tag{C-3a}$$

$$N_t\left(\sum_n (\delta_t - \lambda_{t,n}) A_{\ell,n} + \mu^-_{t,\ell} - \mu^+_{t,\ell}\right) = 0,\ f_{t,\ell} \text{ free},\ \forall t, \ell \in \mathcal{L} \setminus \mathcal{L}^{AC} \tag{C-3b}$$

$$N_t\left(\textstyle\sum_{\ell^{AC}\in\mathcal{L}^{AC}} H_{\ell^{AC},n^{AC}} \gamma_{t,\ell^{AC}} - S_{n^{AC}} \eta_{t,n^{AC}}\right) = 0,\ v_{t,n^{AC}} \text{ free},\ \forall t, n^{AC} \in \mathcal{N}^{AC} \tag{C-4}$$

$$0 \le \beta_{t,n,j,u} \perp N_t(X_{n,j,u} - x_{t,n,j,u}) \ge 0,\ \forall t, n, j, u \tag{C-5}$$

$$N_t\left(f_{t,\ell^{AC}} - \textstyle\sum_{n^{AC}\in\mathcal{N}^{AC}} H_{\ell^{AC},n^{AC}} v_{t,n^{AC}}\right) = 0,\ \gamma_{t,\ell^{AC}} \text{ free},\ \forall t, \ell^{AC} \in \mathcal{L}^{AC} \tag{C-6}$$

$$0 \le \mu^-_{t,\ell} \perp N_t(f_{t,\ell} + K_{t,\ell}) \ge 0,\ \forall t, \ell \tag{C-7}$$

$$0 \le \mu^+_{t,\ell} \perp N_t(-f_{t,\ell} + K_{t,\ell}) \ge 0,\ \forall t, \ell \tag{C-8}$$

$$N_t\left(S_{n^{AC}} v_{t,n^{AC}}\right) = 0,\ \eta_{t,n^{AC}} \text{ free},\ \forall t, n^{AC} \in \mathcal{N}^{AC} \tag{C-9}$$

$$-N_t \textstyle\sum_n \sum_\ell A_{\ell,n} f_{t,\ell} = 0,\ \delta_t \text{ free},\ \forall t \tag{C-10}$$

$$N_t\left(d_{t,n} - \textstyle\sum_i \sum_u x_{t,n,i,u} + \sum_\ell A_{\ell,n} f_{t,\ell}\right) = 0,\ \lambda_{t,n} \text{ free},\ \forall t, n \tag{C-11}$$

$$0 \le \rho \perp Z - \textstyle\sum_t \sum_{n\in\mathcal{N}^{ETS}} \sum_i \sum_u N_t E_{n,i,u} x_{t,n,i,u} \ge 0 \tag{C-12}$$

C.3 MIQP Reformulation

The MPEC in Section 3.2.3 has two types of non-convexities. First, the complementarity conditions arising from the constraints (C-1a)–(C-12) can be circumvented by disjunctive constraints (C-15) - (C-31) (Fortuny-Amat and McCarl, 1981). In effect, we resolve complementarity conditions of the form $0 \leq a \perp b \geq 0$ disjunctively as $a \leq Mw, b \leq M(1-w), a \geq 0, b \geq 0, w \in \{0,1\}$. Here, we choose big-$M$ values in the ranges of 10^6 to 10^7 depending on the constraint in order to avoid unnecessarily restricting the relevant variable. For example, in (C-16), we choose M to be 10^7 so that the net consumption at each node and in each period is not economically restricted. A similar approach was used in Chen et al. (2018) to treat the complementarity constraints of an MPEC. For more guidance on specifying such big-M values, see Gabriel and Leuthold (2010). Second, the bilinear terms in the leader's objective function can be removed by using strong duality from the lower level. In particular, we find the dual problem of the lower level (Dorn, 1960) and verify that strong duality holds (Huppmann and Egerer, 2015) as follows:

$$\begin{aligned}
&\sum_t N_t \Big[\sum_n \Big(D^{int}_{t,n} d_{t,n} - \frac{1}{2} D^{slp}_{t,n} d^2_{t,n} - \sum_j \sum_{u \in \mathcal{U}_{n,j}} C_{n,j,u} x_{t,n,j,u} \Big) \Big] \\
&= \sum_t N_t \Bigg[\sum_n \sum_j \sum_{u \in \mathcal{U}_{n,j}} X_{n,j,u} \beta_{t,n,j,u} + \sum_\ell K_{t,\ell} (\mu^-_{t,\ell} + \mu^+_{t,\ell}) + \sum_n \sum_{u \in \mathcal{U}_{n,s}} \lambda_{t,n} x_{t,n,s,u} \\
&\qquad - \sum_{n \in \mathcal{N}^{ETS}} \sum_{u \in \mathcal{U}_{n,s}} E_{n,s,u} \rho x_{t,n,s,u} \Bigg] + \rho Z
\end{aligned} \tag{C-13}$$

We then use strong duality to express the bilinear terms in the leader's objective function in terms of lower-level primal and dual variables in (C-14), thereby rendering the objective function quadratic.

$$\begin{aligned}
\max_\Phi \quad & \sum_t N_t \Big(\sum_n D^{int}_{t,n} d_{t,n} - \sum_n D^{slp}_{t,n} d^2_{t,n} - \sum_\ell (\mu^-_{t,\ell} + \mu^+_{t,\ell}) K_{t,\ell} - \sum_n \sum_i \sum_u C_{n,i,u} x_{t,n,i,u} \\
& - \sum_n \sum_j \sum_{u \in \mathcal{U}_{n,j}} \beta_{t,n,j,u} X_{n,j,u} \Big) - \rho Z \qquad \text{(C-14)}\\
\text{s.t.} \quad & (11), (C\text{-}3a), (C\text{-}3b), (C\text{-}4), (C\text{-}6), (C\text{-}9), (C\text{-}10), (C\text{-}11) \\
& 0 \leq N_t(-D^{int}_{t,n} + D^{slp}_{t,n} d_{t,n} + \lambda_{t,n}) \leq M r_{t,n}, \ \forall t, n \qquad \text{(C-15)}\\
& 0 \leq d_{t,n} \leq M(1 - r_{t,n}), \ \forall t, n \qquad \text{(C-16)}\\
& 0 \leq N_t \left(-\lambda_{t,n} + C_{n,j,u} + \rho E_{n,j,u} + \beta_{t,n,j,u} \right) \leq \overline{M} \overline{r}_{t,n,j,u}, \ \forall t, j, u \in \mathcal{U}_{n,j}, n \in \mathcal{N}^{ETS} \qquad \text{(C-17)}\\
& 0 \leq N_t \left(-\lambda_{t,n} + C_{n,j,u} + \beta_{t,n,j,u} \right) \leq \overline{M} \overline{r}_{t,n,j,u}, \ \forall t, j, u \in \mathcal{U}_{n,j}, n \in \mathcal{N} \setminus \mathcal{N}^{ETS} \qquad \text{(C-18)}\\
& 0 \leq x_{t,n,j,u} \leq \overline{M}(1 - \overline{r}_{t,n,j,u}), \ \forall t, n, j, u \in \mathcal{U}_{n,j} \qquad \text{(C-19)}\\
& 0 \leq N_t(-f_{t,\ell} + K_{t,\ell}) \leq \hat{M} \hat{r}_{t,\ell}, \ \forall t, \ell \qquad \text{(C-20)}\\
& 0 \leq \mu^+_{t,\ell} \leq \hat{M}(1 - \hat{r}_{t,\ell}), \ \forall t, \ell \qquad \text{(C-21)}\\
& 0 \leq N_t(f_{t,\ell} + K_{t,\ell}) \leq \check{M} \check{r}_{t,\ell}, \ \forall t, \ell \qquad \text{(C-22)}\\
& 0 \leq \mu^-_{t,\ell} \leq \check{M}(1 - \check{r}_{t,\ell}), \ \forall t, \ell \qquad \text{(C-23)}\\
& 0 \leq N_t(X_{n,j,u} - x_{t,n,j,u}) \leq \widetilde{M} \tilde{r}_{t,n,j,u}, \ \forall t, n, j, u \in \mathcal{U}_{n,j} \qquad \text{(C-24)}\\
& 0 \leq \beta_{t,n,j,u} \leq \widetilde{M}(1 - \tilde{r}_{t,n,j,u}), \ \forall t, n, j, u \in \mathcal{U}_{n,j} \qquad \text{(C-25)}\\
& 0 \leq Z - \sum_t \sum_{n \in \mathcal{N}^{ETS}} \sum_i \sum_u N_t E_{n,i,u} x_{t,n,i,u} \leq \underline{M} \underline{r} \qquad \text{(C-26)}\\
& 0 \leq \rho \leq \underline{M}(1 - \underline{r}) \qquad \text{(C-27)}
\end{aligned}$$

$$\underline{r} \in \{0,1\} \quad \text{(C-28)}$$
$$r_{t,n} \in \{0,1\},\ \forall t,n \quad \text{(C-29)}$$
$$\tilde{r}_{t,n,j,u}, \overline{r}_{t,n,j,u} \in \{0,1\},\ \forall t,n,j,u \in \mathcal{U}_{n,j} \quad \text{(C-30)}$$
$$\hat{r}_{t,\ell}, \check{r}_{t,\ell} \in \{0,1\},\ \forall t,\ell \quad \text{(C-31)}$$

where $\Phi = \{d_{t,n}, x_{t,n,i,u}, f_{t,\ell}, v_{t,n^{AC}}, \lambda_{t,n}, \delta_t, \mu^+_{t,\ell}, \mu^-_{t,\ell}, \beta_{t,n,j,u}, \gamma_{t,\ell^{AC}}, \eta_{t,n^{AC}}, \rho, \underline{r}, r_{t,n}, \overline{r}_{t,n,j,u}, \hat{r}_{t,\ell}, \check{r}_{t,\ell}, \tilde{r}_{t,n,j,u}\}$.

References

Chen, Y., M. Tanaka, and A. S. Siddiqui (2018), "Market power with tradable performance-based CO_2 emission standards in the electricity sector," *The Ener. J.* 39: 95–119.

Dorn, W. S. (1960), "Duality in quadratic programming," *Q. Appl. Math.* 18(2): 155–162.

ENTSO-E (2013), *Yearly statistics and adequacy retrospect*, https://docstore.entsoe.eu/Documents/Publications/Statistics/YSAR/141515_YSAR_2013_report.pdf.

EU (2012), *Gazzetta ufficiale dell'Unione Europea*, https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=OJ:L:2012:181:FULL&from=IT.

Eurostat (2014), *Electricity and heat statistics*, http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat_statistics.

Fortuny-Amat, J. and B. McCarl (1981), "A representation and economic interpretation of a two-level programming problem," *J. Oper. Res. Soc.* 32(9): 783–792.

Gabriel, S. A. and F. U. Leuthold (2010), "Solving discretely-constrained MPEC problems with applications in electric power markets," *Ener. Econ.* 32: 3–14.

Huppmann, D. and J. Egerer (2015), "National-strategic investment in European power transmission capacity," *Eur. J. Oper. Res.* 247: 191–203.

Terna (2013), *Dati provvisori esercizio 2013*, http://download.terna.it/terna/0000/0118/52.pdf.