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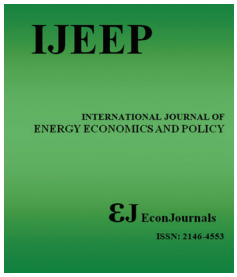

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Focus on the Performances of the Most Advanced Italian Thermoelectric Power Plants

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ABSTRACT

The key indicators, in the Annex IV of Regulation (EC) 1221/2009 ("EMAS III"), should permit an assessment of the environmental impact of an organization, through the quantification of resources and the evaluation of significant environmental aspects. The aim of this research is to carry out a brief survey on the suitable use and reporting of the performance indicators in the EMAS environmental statements of a very representative sample of Italian combined cycle gas turbine (CCGT) power plants and then on the state and evolution of few core energy and environmental indicators in order to investigate their benchmarking performances. Our findings are that the total consumption of fossil fuels and the overall emissions have greatly decreased in relation to the less operating time of the CCGT power stations, but, in relation to the electricity produced, the consumption of natural gas and the emissions of greenhouse gases have drastically increased.

Keywords: Combined Cycle Gas Turbine Power Stations, EMAS Environmental Statement, Performances
JEL Classifications: L940, Q310, Q41

1. INTRODUCTION

In Italy, and in the rest of world, the use of fossil fuels, for electricity production, covers most of the domestic power generation and energy demand "World Energy Council (2013)". The adoption of an environmental management system (EMS), like the EMAS Regulation, is of fundamental importance for those, especially, resource-intensive industrial sectors with significant environmental implications, such as electric energy generation ones; this is needed for monitoring their performances, for motivating them to continuous audit and improvement and for the implementation of better management and benchmarking practices "Testa et al., (2014)".

Despite the modernization and performance upgrading of the national thermoelectric industry – in particular of the combined cycle gas turbine (CCGT) power plants – which has been taking place already for several years "Montanari (2004)", the severe economic crisis has had serious repercussions on productivity, plant utilization quotas and, therefore, on the efficiency of the whole sector. As that will also result from this paper, the downturn of electricity generation, accentuated in particular since 2012, is affected by the lower electricity demand subsequent to the national economic crisis and also to the ever-increasing contribution of alternative and renewable energy sources, in particular photovoltaic systems.

CCGT system, which uses natural gas as fuel, is considered, among those traditional sources, the best available technology for electricity generation, owing to its high energy efficiency (over 50%) and its reduced environmental impact. As it is well known, this technology is based on the combined application of two thermodynamic cycles in successive phases (Rankine and Brayton cycles) with gas and steam turbines.

This research has been conducted with the aim to carry out a brief survey on the suitable use and report of the performance indicators in the EMAS Environmental Statements of a very representative sample of Italian CCGT power stations and then, in greater detail, on the current production of the same sample and their historical and benchmarking performances regarding fuel consumption (energy efficiency) and CO_2 emissions (environmental efficiency) during a serious economic recession and strong reduction of energy demand.

2. MATERIALS AND METHODS

This 10-years analysis goes from 2007 to 2016, that is the year of the last available data (where not otherwise indicated) published in the EMAS environmental statements by the largest part of the statistical sample taken into consideration. It was decided to restrict the investigation to only CCGT power plants because they represent the most advanced and efficient way to produce electricity by fossil fuels. Besides, our focus was on the analysis of those CCGT installations exclusively equipped with gas-turbine groups, excluding those ones with multi-fuel electric generators, which use other fuels (coal, fuel oil).

The research methodology adopted for this work uses the statistical techniques of non-probabilistic sampling, which allow selection criteria of convenience according to the predetermined objective. In particular, it was decided to adopt non-probabilistic sampling for quotas, qualifying them in terms of specific characteristics of the power stations.

CCGT plants have been selected from the EMAS registered organizations databases at the ISPRA (2018) and European Commission (2018) websites arranged according to the following statistical classification of economic activities: NACE Rev. 2 of EC Regulation No. 1893/2006. From this database we have proceeded in this way: (1) Extrapolation of those organizations having the NACE code 35.11 (electricity generation); (2) extraction of thermoelectric power plants; (3) adoption of the following sub-criteria: (a) Combined cycle gas plants; (b) plants with installed power ≥100 MW; (c) selection of those plants with, at least, three available years of environmental statements.

The following 31 CCGT thermoelectric power plants of several companies have therefore been examined (in brackets: organization, installed power and eventually different indication of the period considered): Altomonte (Edison, 125 MW, excluding 2016), Amaldi (Enel, 1,400 MW), Archimede (Enel, 750 MW), Brindisi (Enipower, 1,321 MW, excluding 2007, 2008 and 2009), Bussi sul Tirino (Edison, 125 MW, excluding 2015 and 2016), Candela (Edison, 360 MW, excluding 2016), Cassano d'Adda (A2A Gencogas, 995 MW), Chivasso (Edipower-A2A, now A2A Gencogas, 1,440 MW), Ferrara (Enipower, 840 MW, excluding 2007 and 2008), Ferraris (Enel, 700 MW), Jesi (Edison, 130 MW), Mantova (Enipower, 836 MW), Marghera Levante (Edison, 766 MW, excluding 2016), Mincio (A2A Gencogas, 380 MW), Moncalieri (Iren Energia, 800 MW), Ostiglia (E.ON, now EP Produzione, 1,482 MW), Piacenza (Edipower, now A2A Gencogas, 840 MW), Porto Corsini (Enel, 750 MW, excluding 2007), Ravenna (Enipower, 972 MW), San Quirico Trecasali (Edison, 125 MW), Santa Barbara (Enel, 390 MW), Sarmato (Edison, 180 MW, excluding the years from 2014 to 2016), Scandale (A2A-EPH [Ergosud], 835 MW, from 2010 to 2016), Sermide (Edipower, now A2A Gencogas, 1,140 MW), Simeri Crichi (Edison, 857 MW, excluding 2007 and 2016), Tavazzano e Montanaso (E.ON, now EP Produzione, 1,440 MW), Terni (Edison, 100 MW), Torrevaldaliga Nord (Tirreno Power, 1,520 MW), Torviscosa (Edison, 790 MW, excluding 2016), Turbigo (Edipower, now IREN Energia, 1,775 MW, from 2010), Verzuolo (Edison, 120 MW, excluding 2016). Considering the whole 10-year period, the shutdown (S/D) or not in operation (N/O) years and the not-available (N/A) reports, the environmental statements examined have been 261 in total, taken predominantly from ISPRA or producers' web pages (A2A Gencogas, 2018; Edison, 2018; Enel, 2018; Enipower, 2018; EP Produzione, 2018; Ergosud, 2018; Iren Energia, 2018). All these plants represent a share exceeding 65% of the installed power generation capacity (22.8 TW) of the whole national thermoelectric sector.

The above-listed plants have been grouped, according to the installed power capacity, into three categories/sizes: (1) no. 9 small plants (from 100 to 500 MW), (2) no. 14 medium-sized plants (from 501 to 1000 MW) and (3) no. 8 large-scale plants (from 1001 to 1775 MW).

In order to simplify the analysis, reducing it only to the variables that are really important for assessing the sustainability of the production process, it was decided to examine only two indicators, the most important ones and those always present: (1) one pertaining to energetic performances of natural gas ($sm^3 \times 1000/GWh$) and (2) another one related to environmental performances in terms of greenhouse gases emissions (t/GWh). This is because the comparison between the production sites on the basis of other indicators was found to be too difficult and not very meaningful. In fact, in some cases, the relevant data were not always available and, in other cases, the values were very divergent, not only between different companies or generation sites but also for the same site in different years.

For the energy efficiency index ([consumption of fuel]/[energy produced]), it was chosen, for not distorting the benchmark analysis, to exclude the amount of thermal energy produced by subsidiary energy recovery systems, because the aim of a thermoelectric plant is not to produce heat but electricity.

For the environmental analysis, the total emissions of greenhouse gases have been considered, in terms of tons of equivalent CO_2, in relation to the GWh of electricity produced. NOx, SO_2, CO and PM_{10} emissions, alone, have been excluded from this benchmarking analysis because they have been considered negligible for their related small quantities.

2.1. Some Preliminary Considerations about EMAS Environmental Statements Content

We have found, at first, that all the EMAS key performance indicators (energy efficiency, material efficiency, water consumption, waste generation and atmospheric emissions), as reported in the Annex IV of the Regulation, are referred, very

often, to the gross electricity production, although we believe that it would be best to consider the net electrical output, excluding electrical losses and the energy consumed for starting the auxiliary equipment (pumps, valves, fans, etc.).

All the specific performance indicators are not always reported in the same way: for example, sometimes, the energy efficiency index, about the specific consumption of methane, is expressed in "m^3/GWh," or "MWh/MWh," or even by a percentage of "Gross electrical energy/Energy of methane" or in terms of "kcal/kWh" or "GJ/GWh". Besides, in some cases, the absolute fuel consumptions are not given. Therefore, in order to perform the necessary inter-sites comparisons and consolidations of data, it has been necessary for us to standardize the related measurement units adopting the appropriate equivalence.

For those production plants that use different fuels (such as natural gas and oil), in some cases, it is quite impossible, according to the environmental summary table of EMAS statements and the associated indicators, to identify the electricity production portion and environmental contribution of each production unit.

Analysing different statements, moreover, it has been clear that, to date, there is not a unique way to calculate the performance indicators. For example, some organizations, consider as "produced energy" also the waste heat conveyed to the heating systems of residential areas, distorting thereby the amount of quotients of fuel consumption.

More specifically, as regards the CCGT cogeneration power plants, it has been necessary, therefore, to recalculate the performance indicators referring them exclusively to the electrical net generation by separating, for example, the share of recovered heat for power generation and the thermal energy used for domestic heating by co-generation; this needs to occur in order to homogenize and not distorting the comparison with other organizations invalidating the data relating to the electric power production.

For some situations, we do not understand why, from one year to another, the performance indexes of raw materials (hydrochloric acid, sodium hydroxide, etc.) and the amount of waste, especially of hazardous ones, significantly, assume very different values. And, in this regard, no reasons are provided. In some cases, the performance indicators, relating to the use of materials in relation to energy produced, are not calculated.

Under the term of "Material efficiency" in the environmental statements, rather than individually listing the indicators of the different raw substances used, sometimes, they are grouped in categories such as "Other consumable materials" or "Consumable chemicals". Moreover, in some environmental reports there is not any indication of net electricity production and this does not allow researches to calculate the utilization factor of a plant or to know the environmental impact or to determine other indicators about the use of other raw materials.

In some cases, in the section of the Environmental Summary, specific data and indexes are not always present (i.e., those of "Biodiversity" or "Use of land" and "Hazardous waste production"), claiming the generic reason that they are not related to significant environmental aspects of the specific production facility.

Furthermore, some companies do not report the "Summary table" of their environmental statements: this does not facilitate a production benchmarking and environmental assessment between different plants and companies. Often, this section, where present, does not provide explicit input and output data of previous years, so it is not possible to make immediate comparisons by examining a single statement.

In some statements, for the item "Total emissions of greenhouse gases", only the information about CO^2 emissions are given, thus omitting the contribution, although very modest, of other greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons (HFCs), hydro-chlorofluorocarbons (HCFCs), sulphur hexafluoride (SF^6), etc. Moreover, the indicator of CO_2 emissions per GWh_e produced is not always reported.

It is necessary, therefore, greater expertise and skills of environmental verifiers, during the revision process of a statement, are necessary to avoid of affecting the fundamental EMAS communication aims. Also, for a better completion of information, it would be desirable, for obvious reasons, to have data about environmental indicators of single productive modules/groups of a specific power plant available, rather than those of a whole production site.

3. RESULTS AND DISCUSSION

Below, we have inserted the Tables 1, 2 and 3 related to the data sources of the CCGT power plants examined, grouped, as we have anticipated above, in three-dimensional classes: small, medium and large plants.

Immediately after these ones, we have inserted Table 4, which is the processing and the synthesis of these first three tables.

In Table 5, in order to extend our analysis to the entire Italian context, the annual values of other national important variables are inserted: gross domestic product (GDP), thermoelectric production, production of electricity from renewables, electricity demand and so on.

After all, in Table 6, we have calculated the corresponding correlation indexes of the variables of Table 5, in order to make an immediate and reciprocal comparison.

From 2007 to 2016, the total electricity production of all the CCGT plants examined has significantly fallen (Table 4): from 85.1 TWh_e (it was even 86.3 in 2008) to the last 39.5 TWh_e. During this period, there have been only three production peaks (2008, 2010 and 2015), corresponding to an increase of demand and to the entry into operation of new power stations. The plants that have suffered the most significant reduction in electricity production have been the small-sized ones (from 11.2 in 2007 to 3.7 TWh_e in 2015, not

Table 1: Small-sized plants: net electricity production, energy efficiency and environmental efficiency

	U.M.	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BUSSI SUL TIRINO (EDISON) - 125 MW											
Net electricity production	GWh_e	930	1,043	970	215	88	186	126	104	N/A	N/A
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	236.6	229.2	233.5	239.5	246.4	230.0	234.0	246.6	N/A	N/A
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	447.0	434.0	413.0	435.0	469.0	444.0	453.0	481.0	389.3	N/A
CANDELA (EDISON) - 360 MW											
Net electricity production	GWh_e	2,377	2,087	2,394	2,353	2,222	2,566	2,180	2,300	2,482	N/A
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	190.6	188.8	190.1	190.0	189.9	190.4	190.4	190.4	189.8	N/A
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	509.9	550.0	396.0	397.8	400.5	401.4	402.1	402.3	397.8	N/A
JESI (EDISON) - 130 MW											
Net electricity production	GWh_e	1,037	1,080	915	997	96	136	S/D	S/D	S/D	S/D
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	229.5	224.1	223.0	224.7	250.0	247.5	S/D	S/D	S/D	S/D
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	416.0	415.0	420.0	423.0	470.7	468.0	S/D	S/D	S/D	S/D
MINCIO (A2A Gencogas) - 380 MW											
Net electricity production	GWh_e	1,675	1,657	1,262	897	884	608	416	204	393	34
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	201.1	204.7	202.7	202.0	204.7	203.5	209.0	226.9	208.7	207.5
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	378.1	403.2	385.1	383.0	389.3	388.9	402.5	435.4	405.4	400.4
SANTA BARBARA (ENEL) - 390 MW											
Net electricity production	GWh_e	1,939	1,557	1,107	854	541	184	191	41	143	847
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	186.2	187.5	198.3	195.6	205.5	217.7	226.3	270.7	224.7	192.7
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	380.0	382.0	399.3	400.5	404.8	443.9	450.2	532.0	442.1	394.1
SAN QUIRICO (EDISON) - 125 MW											
Net electricity production	GWh_e	933	989	1,046	966	220	113	78	20	S/D	S/D
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	236.9	237.6	237.1	238.1	254.5	265.4	277.3	284.7	S/D	S/D
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	N/A	391.0	393.0	476.0	506.0	499.0	542.0	S/D	S/D
SARMATO (EDISON) - 180 MW											
Net electricity production	GWh_e	946	457	22	19	40	257	22	S/D	S/D	S/D
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	223.0	225.4	334.3	324.9	256.3	228.3	241.0	S/D	S/D	S/D
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	429.0	433.0	634.0	632.0	499.0	437.0	464.0	S/D	S/D	S/D
TERNI (EDISON) - 100 MW											
Net electricity production	GWh_e	608	642	627	500	392	S/D	94	88	73	S/D
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	223.7	222.7	221.7	228.0	229.6	S/D	285.1	237.5	242.5	S/D
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	N/A	336.0	324.0	352.0	S/D	503.0	454.0	468.0	S/D
VERZUOLO (EDISON) - 120 MW											
Net electricity production	GWh_e	799	781	764	800	814	811	701	698	625	N/A
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	250.3	252.2	243.5	246.3	246.9	249.1	258.2	255.0	262.4	N/A
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	N/A	308.0	299.0	293.0	304.0	298.0	305.0	304.0	N/A

N/A: Not available, N/O: Not in operation, S/D: Shutdown. Sources: Our elaboration on companies data of EMAS Environmental Statements, several years

considering the less significant 2016 data, because for this last year there have been few EMAS Environmental Statements for this group) and the large-sized plants, whose production has more than halved: from 36.5 to 16.9 TWh_e. The medium-sized plants, more than others, have absorbed the shock of the reduction of electricity demand better, limiting the production decrease to less than 40%: from 37.4 to 21.8 TWh_e. It is possible that these plants are, among all, the most cost-effective even in under-used facilities situations.

During the entire period, medium-sized plants have also been those that, on average, contributed for the most part (55.2%) to total electricity production of CCGT national systems. After these plants, there are the big-sized ones (36.5%) and, lastly, the small ones (9.9%).

Always from Table 4, we can see that the average annual production of the plants in operation has a very negative trend from 2007 to 2014 (from 3,405 to 1,486 GWh_e per plant); subsequently it has slightly increased during the last two years. The 10-year average production of all plants is 2,285 GWh_e/y/plant. Since 2012, the average production of medium-sized sites has been significantly constant, above the others, probably because they are better able to adapt their production to the needs of the electricity demand.

Considering the total installed capacity of the plants, we have calculated the following performance indicators: (1) The annual operating hours of each group of plants (as [produced electricity]/[installed capacity]) and (2) the related operating percentage per year, dividing the above operating hours by 8,760 (h in a year). The average ten-year value of the first indicator, for all plants, is 2,828 h/year, equal to an operating rate of 32.3%. The plants that have a higher operating percentage are the small-sized ones and those of medium size, both around 38%, while the large plants have a limited operating percentage (25.5%). Examining the historical evolution of this indicator, it is clear that the operating hours basically follow the same decisive descending trend of production, recording a decrease of almost 60% (from 4,587 to 1,988 h/year), with a slight stabilization, around the average value of 1,750 h/years, only in the last four years. Also in the case of the second indicator, the plants that, from 2007 to 2014, have the most significant decreases are the large-sized ones, whose operating percentage – constantly below all the groups of plants – has gone from 50% to about a quarter (12.8%); this percentage has slightly risen during the subsequent two years. The group that, in the last 6 years, has the highest operating quotas is that of medium-sized plants, with an annual average of 33.1%.

Table 2: Medium-sized plants: net electricity production, energy efficiency and environmental efficiency

	U.M.	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
ALTOMONTE (EDISON) - 780 MW											
Net electricity production	GWh_e	4,080	3,475	1,921	2,035	1,518	2,223	1,407	1,201	2,776	N/A
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	191.9	194.5	197.2	196.4	200.9	196.5	200.2	199.2	197.1	N/A
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	373.5	379.6	384.7	384.0	392.2	383.0	394.3	393.2	389.3	N/A
ARCHIMEDE (ENEL) - 750 MW											
Net electricity production	GWh_e	4,609	4,210	4,050	3,447	3,643	3,460	3,722	3,451	3,162	2,004
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	150.8	148.9	152.8	159.8	196.8	194.5	193.7	196.8	201.5	206.1
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	387.1	385.3	395.8	412.8	399.7	398.6	378.0	403.9	411.8	422.7
CASSANO D'ADDA (A2A Gencogas) - 995 MW											
Net electricity production	GWh_e	4,461	3,846	2,981	2,701	2,464	1,410	796	680	588	761
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	203.8	202.2	205.3	201.6	204.3	205.8	212.7	225.1	226.7	217.9
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	395.0	392.0	397.7	394.4	393.2	396.5	412.0	434.0	423.0	414.0
FERRARA (ENIPOWER) - 840 MW											
Net electricity production	GWh_e	N/A	N/A	2,188	2,703	3,033	4,246	3,457	3,016	3,152	3,991
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	N/A	N/A	117.8	169.8	128.6	199.2	200.4	203.0	208.8	202.8
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	N/A	228.8	425.1	392.7	383.4	385.1	390.7	405.7	398.1
FERRARIS (ENEL) - 700 MW											
Net electricity production	GWh_e	566	855	312	S/D	S/D	S/D	S/D	S/D	S/D	S/D
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	233.2	229.2	240.4	S/D	S/D	S/D	S/D	S/D	S/D	S/D
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	477.0	463.0	483.0	S/D	S/D	S/D	S/D	S/D	S/D	S/D
MANTOVA (ENIPOWER) - 836 MW											
Net electricity production	GWh_e	4,516	4,227	4,728	4,146	4,144	4,395	3,808	3,686	3,746	3,772
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	234.9	223.6	217.0	225.0	224.2	222.8	231.9	231.7	194.2	193.4
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	444.3	420.9	412.0	433.2	429.1	428.4	448.3	446.5	451.3	449.8
MARGHERA LEVANTE (EDISON) - 766 MW											
Net electricity production	GWh_e	3,913	2,571	2,582	2,353	1,962	2,169	2,196	1,248	2,221	N/A
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	229.0	221.0	198.1	216.1	203.9	214.0	211.8	209.3	210.1	N/A
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	343.0	376.0	366.0	361.0	368.0	406.0	401.0	404.0	N/A
MOCALIERI (IREN Energia) - 800 MW											
Net electricity production	GWh_e	2,354	2,848	3,679	4,005	4,433	3,621	3,982	2,691	2,382	2,980
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	219.0	217.3	202.5	199.8	197.2	204.0	204.3	212.0	205.6	203.1
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	436.7	424.1	398.7	392.0	385.2	396.9	395.3	410.5	403.7	398.4
PIACENZA (A2A Gencogas) - 840 MW											
Net electricity production	GWh_e	3,204	3,024	2,582	2,353	1,962	1,667	842	636	1,073	788
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	195.6	197.0	198.0	195.1	198.7	201.9	205.3	213.8	204.9	201.8
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	378.3	379.6	384.7	385.3	384.8	390.0	396.8	371.8	399.8	397.1
PORTO CORSINI (ENEL) - 750 MW											
Net electricity production	GWh_e	N/A	4,776	2,627	2,957	2,778	1,482	190	69	91	1,072
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	N/A	198.7	200.2	202.9	201.2	203.8	224.2	239.1	256.0	205.0
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	370.0	376.9	381.1	385.0	387.0	427.0	456.0	492.0	393.0
RAVENNA (ENIPOWER) - 972 MW											
Net electricity production	GWh_e	5,538	4,751	4,694	4,683	4,848	4,601	4,395	3,743	3,943	4,236
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	214.5	218.5	221.1	223.8	221.9	221.0	216.3	222.5	225.6	216.1
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	397.8	406.0	413.9	420.9	424.3	418.2	409.1	423.7	429.2	409.0
SCANDALE (A2A-EPH) - 835 MW											
Net electricity production	GWh_e	N/O	N/O	N/O	0,448	1,489	840	556	241	635	2,169
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	N/O	N/O	N/O	198.8	190.5	193.4	202.3	210.0	201.6	189.8
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/O	N/O	N/O	434.8	359.3	363.3	384.0	397.1	382.9	364.3
SIMERI CRICHI (EDISON) - 857 MW											
Net electricity production	GWh_e	N/A	3,462	2,717	2,439	2,409	2,119	2,426	2,521	2,731	N/A
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	N/A	186.9	188.8	191.1	191.8	190.4	190.4	191.2	191.5	N/A
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	356.0	360.0	370.0	373.0	369.0	374.0	375.0	376.0	N/A
TORVISCOSA (EDISON) - 790 MW											
Net electricity production	GWh_e	4,174	3,963	4,048	4,007	3,244	3,298	2,244	2,178	2,093	N/A
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	187.6	190.8	191.0	191.9	195.4	194.4	201.0	201.6	202.1	N/A
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	356.0	361.0	349.0	350.0	353.0	352.0	359.0	359.0	360.0	N/A

N/A: Not available, N/O: Not in operation, S/D: Shutdown. Sources: Our elaboration on companies data of EMAS Environmental Statements, several years

The index of fuel average consumption on the net electricity produced of all plants has basically grown from 2007 to 2014: from 208.5 to 220.5 $sm^3 1000/GWh_e$. It has slightly decreased only during the last two years, due to an increase of electricity production and to a lower number of small plants in operation, which are the least efficient ones. During the decade, the global average of fuel consumption was 211.3 $sm^3 1000/GWh_e$. Small plants are those that constantly burn, compared to all the others, more natural gas (+15%) for the same electricity output. The ten-year average of these plants is, in fact, equal to 227.4 $sm^3 1000/GWh_e$ compared to around 203 $sm^3 1000/GWh_e$ of medium and large ones.

Table 3: Large-sized plants: net electricity production, energy efficiency and environmental efficiency

AMALDI (ENEL) - 1.400 MW	U.M.	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Net electricity production	GWh_e	6,490	7,404	3,503	5,299	5,030	2,634	684	390	504	2,735
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	191.4	191.1	197.0	195.1	194.8	202.4	226.6	235.9	230.2	196.0
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	377.0	375.9	389.4	387.4	381.9	393.7	441.5	459.0	452.4	385.7
BRINDISI (ENIPOWER) - 1.321 MW											
Net electricity production	GWh_e	N/A	N/A	N/A	7,132	5,954	5,874	5,431	5,004	5,257	6,104
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	N/A	N/A	N/A	187.6	192.5	191.5	182.8	182.5	183.0	179.4
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	N/A	N/A	378.0	393.9	393.8	370.2	370.4	375.5	390.9
CHIVASSO (A2A Gencogas) - 1.440 MW											
Net electricity production	GWh_e	5,479	4,816	2,990	2,280	2,390	1,950	580	S/D	355	933
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	193.1	194.3	191.0	192.0	170.0	199.5	200.9	S/D	208.0	199.7
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	378.7	379.0	385.0	388.0	387.0	388.0	392.5	S/D	405.8	391.9
OSTIGLIA (EP Produzione) - 1.482 MW											
Net electricity production	GWh_e	6,337	5,864	2,834	3,170	4,207	3,097	2,426	1,485	2,284	2,456
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	193.1	197.0	210.3	204.2	196.6	200.5	203.7	210.1	199.8	195.7
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	381.5	391.4	418.9	407.3	390.0	398.0	393.0	404.0	388.0	381.0
SERMIDE (A2A Gencogas) - 1.140 MW											
Net electricity production	GWh_e	4,959	4,595	2,652	2,969	1,989	1,375	1,103	504	927	819
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	199.9	200.1	207.1	203.6	207.2	210.4	214.3	232.8	218.8	221.7
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	595.0	603.0	647.0	643.0	650.0	664.0	683.0	754.0	707.0	720.0
TAVAZZANO E MONTANASO (EP) - 1.440 MW											
Net electricity production	GWh_e	6,511	5,201	3,166	2,569	2,018	1,544	3,546	1,912	2,345	1,795
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	197.5	201.5	208.5	205.1	207.6	207.9	198.3	207.6	200.0	202.8
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	407.0	417.0	425.0	404.0	406.0	408.0	387.0	388.0	380.0	385.0
TORREVALD. (TIRRENO POWER) - 1.520 MW											
Net electricity production	GWh_e	6,696	6,109	4,158	2,600	2,703	1,130	1,308	1,062	781	112
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	200.1	205.4	214.5	222.3	212.0	215.0	212.5	209.0	213.8	416.3
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	416.8	420.7	437.2	458.1	429.5	438.1	434.3	420.9	428.9	94.6
TURBIGO (IREN Energia) - 1.755 MW											
Net electricity production	GWh_e	N/A	N/A	N/A	2,347	2,151	1,594	923	962	1,615	1,932
Fuel consumption on net electricity produced	$sm^3 1000/GWh_e$	N/A	N/A	N/A	202.2	201.5	202.4	206.5	209.6	198.9	201.7
Total emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	N/A	N/A	N/A	401.2	398.3	399.2	404.9	410.4	393.7	397.3

N/A: Not available, N/O: Not in operation, S/D: Shutdown. Sources: Our elaboration on companies data of EMAS Environmental Statements, several years

The other index, referred to the average emissions of greenhouse gases (CO_2-eq) on net electricity (GWh_e) produced, assumes, from 2007 to 2014, a strongly increasing trend, that is correspondingly similar to the energy efficiency index trend: from 350.5 to 430.4 t CO_2-eq/GWh_e. On average, during the decade, the value of this index is 401.6 t CO_2-eq/GWh_e. Large plants have a 10-year average greenhouse gas emission index that is much higher than the others (428 t CO_2-eq/GWh_e/y), probably due to their lower operation rate and to their continuous on/off cycles. In fact, medium-sized plants have, on average, emitted lower quantities of greenhouse gases (396.5 t CO_2-eq/GWh_e/y), due to their longer operating and less discontinuous generation cycles.

An interesting analysis concerns the calculation of correlation indexes (Table 6) between the items of Table 5. For this purpose, we have used the subsequent equation for the calculation of the several correlation coefficients:

$$\rho_{X,Y} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2(y-\bar{y})^2}} \quad (1)$$

Where x and y are the values of the variables of two series and and are the respective average values.

Considering the variations of the values of the historical series of CCGT production, the corresponding variations of the other variables identified in Table 5 and the reciprocal correlations, we have prepared the Table 6, from which, we can predictable see that a high correlation value occurs between the variations of GDP (*e*) and the variations of the consumption of electric energy (*f*) (P = 0.932).

By calculating the corresponding correlation indexes, it appears that changes of electricity demand (*f*) are not strongly connected to the total electricity production (*i*), both from traditional energetic

Table 4: All plants: net electricity production, energy efficiency and environmental efficiency

	U.M.	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
1) SMALL-SIZED PLANTS											
A) Net electricity production	GWh_e	11,244	10,293	9,107	7,601	5,297	4,861	3,808	3,455	3,716	881
B) Fuel average consumption on net electricity produced	$sm^3 1000/GWh_e$	219.8	219.1	231.6	232.1	231.6	229.0	240.2	244.5	225.6	200.1
C) Average emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	426.7	436.2	409.2	409.7	417.1	424.1	434.0	450.3	401.1	397.3
D) Average production of electricity per plant	$GWh_e/year/unit$	1,249	1,144	1,012	845	589	608	476	494	619	441
E) Total installed capacity	*GW*	1.910	1.910	1.910	1.910	1.910	1.810	1.780	1.600	1.350	0.770
F) Operating hours per year (F = A/E)	*No.*	5,887	5,389	4,768	3,980	2,773	2,686	2,139	2,159	2,753	1,144
G) Operating percentage per year (G = F/8760)	*%*	67.2	61.5	54.4	45.4	31.7	30.7	24.4	24.7	31.4	13.1
2) MEDIUM-SIZED PLANTS											
A) Net electricity production	GWh_e	37,415	42,008	39,109	37,829	37,927	35,531	30,021	25,361	28,593	21,773
B) Fuel average consumption on net electricity produced	$sm^3 1000/GWh_e$	206.0	202.4	194.6	197.9	196.6	203.2	207.3	211.9	209.7	204.0
C) Average emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	405.1	390.0	381.6	396.1	387.1	387.3	397.6	404.8	409.9	405.2
D) Average production of electricity per plant	$GWh_e/year/unit$	3,742	3,501	3,008	2,910	2,917	2,733	2,309	1,951	2,199	2,419
E) Total installed capacity	*GW*	8.229	9.836	10.676	10.811	10.811	10.811	10.811	10.811	10.811	7.618
F) Operating hours per year (F = A/E)	*No.*	4,547	4,271	3,663	3,499	3,508	3,287	2,777	2,346	2,645	2,858
G) Operating percentage per year (G = F/8760)	*%*	51.9	48.8	41.8	39.9	40.0	37.5	31.7	26.8	30.2	32.6
3) LARGE-SIZED PLANTS											
A) Net electricity production	GWh_e	36,472	33,989	19,303	28,366	26,442	19,198	16,001	11,319	14,068	16,887
B) Fuel average consumption on net electricity produced	$sm^3 1000/GWh_e$	195.8	198.2	204.7	201.5	197.8	203.7	205.7	185.9	206.6	226.7
C) Average emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	426.0	431.2	450.4	433.4	429.6	435.3	438.3	400.8	441.4	393.3
D) Average production of electricity per plant	$GWh_e/year/unit$	6,078.7	5,664.8	3,217.2	3,545.8	3,305.3	2,399.8	2,000.1	1,617.0	1,758.5	2,110.8
E) Total installed capacity	*GW*	8.422	8.422	8.422	11.498	11.498	11.498	11.498	10.058	11.498	11.498
F) Operating hours per year (F = A/E)	*No.*	4,331	4,036	2,292	2,467	2,300	1,670	1,392	1,125	1,224	1,469
G) Operating percentage per year (G = F/8760)	*%*	49.4	46.1	26.2	28.2	26.3	19.1	15.9	12.8	14.0	16.8
4) TOTAL											
A) Net electricity production	GWh_e	85,131	86,290	67,519	73,796	69,666	59,590	49,830	40,135	46,377	39,540
B) Fuel average consumption on net electricity produced	$sm^3 1000/GWh_e$	208.5	207.1	208.7	209.1	207.4	210.5	215.9	220.5	211.8	213.1
C) Average emissions of greenhouse gases	$t\ CO_2\text{-}eq/GWh_e$	350.5	366.1	405.2	410.1	407.4	410.7	418.9	430.4	417.3	399.3
D) Average production of electricity per plant	$GWh_e/year/unit$	3,405	3,196	2,411	2,460	2,322	2,055	1,718	1,486	1,718	2,081
E) Total installed capacity	*GW*	18.561	20.168	21.008	24.219	24.219	24.119	24.089	22.469	23.659	19.886
F) Operating hours per year (F = A/E)	*No.*	4,587	4,279	3,214	3,047	2,877	2,471	2,069	1,786	1,960	1,988
G) Operating percentage per year (G = F/8760)	*%*	52.4	48.8	36.7	34.8	32.8	28.2%	23.6	20.4	22.4	22.7

Sources: Our elaboration on companies data of EMAS Environmental Statements, several years

Table 5: Italy: GDP, demand and production of electricity

	U.M.	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
a) Electricity from CCGT*	GWh_e	85,131	86,290	67,519	73,796	69,666	59,590	49,830	40,135	46,377	39,540
b) Average CCGT electricity production	GWh_e/year/plant	3,405	3,196	2,411	2,460	2,322	2,055	1,718	1,486	1,718	2,081
c) Fuel average CCGT consumption	$sm^3/1000/GWh_e$	208.5	207.1	208.7	209.1	207.4	210.5	215.9	220.5	211.8	213.1
d) Average CCGT greenhouse emissions	$t\ CO_2$-eq/GWh_e	350.5	366.1	405.2	410.1	407.4	410.7	418.9	430.4	417.3	399.3
e) GDP**	Billion €	1,687	1,669	1,578	1,605	1,614	1,568	1,541	1,543	1,554	1,551
f) National demand of electricity	GWh	318,953	319,037	299,915	309,885	313,792	307,220	297,288	291,084	297,180	295,508
g) Thermoelectric production°	GWh	196,197	180,559	164,461	162,828	164,495	163,564	154,247	146,957	157,119	172,282
h) Electricity from renewables°°	GWh	47,899	58,154	69,255	76,964	82,962	92,222	112,008	120,679	108,904	108,022
i) Total electricity production (a+d+e)	GWh	319,232	325,003	301,235	313,588	317,123	315,375	310,654	302,767	307,143	313,740

*Net production, **GDP at market prices - billion euros (chained values; reference year=2010), °Gross production (minus CCGT), °hydroelectric, wind, photovoltaic, geothermal, bioenergy (including MSW). Sources: Our elaboration on data of Terna, Dati Statistici sull'energia elettrica in Italia, https://www.terna.it/it-it/sistemaelettrico/statisticheprevisioni/datistatistici.aspx [Accessed 12.5.2018]; ISTAT, Serie storiche - Conti economici nazionali, http://seriestoriche.istat.it/index.php [Accessed 27.5.2018]; CCGT EMAS Environmental Statements, several years

Table 6: Correlation indexes between the items of Table 5

Variables	Correlation
a) & b)	0.913
a) & c)	–0.811
a) & d)	–0.760
a) & e)	0.926
a) & f)	0.935
a) & g)	0.710
a) & h)	–0.959
a) & i)	0.632
b) & c)	–0.763
b) & d)	–0.945
c) & d)	0.617
e) & f)	0.932
e) & g)	0.854
e) & h)	–0.917
e) & i)	0.732
f) & g)	0.754
f) & h)	–0.870
f) & i)	0.831
g) & h)	–0.819
g) & i)	0.698
h) & i)	–0.552

Sources: Our elaboration on data of Table 5

sources (*g*) and from renewables (*h*). Instead the correlation between (*f*) and the annual variations of electricity production from CCGT plants (*a*) is very high (P = 0.935), probably, because these plants succeed in making their production more flexible, adapting their operation, better and faster than others, to the demand variations.

The variations of electricity production from CCGT plants (*a*) are strongly, and inversely, related to the corresponding variations of electricity production from renewables (*h*) (P = −0.959), probably because both these different sources are in direct competition in order to satisfy the same daily load peaks of electricity demand; the CCGT series (*a*) is significantly connected to the annual changes of GDP (*e*) (P = 0.926) too, but less connected to the changes of the remaining thermoelectric production (*g*) (P = 0.710). All that clearly suggests that the contraction of CCGT production took place mainly due, in order of decreasing importance, to: (1) The increase of the production share from renewables; (2) the contraction of national electricity demand and (3) to the reduction of GDP.

Another interesting technical aspect comes from the correlation indexes between the annual average CCGT production per plant (*b*) and the average annual fuel consumption and environmental efficiency indexes (*c, d*): in fact, the variations of annual electricity production are limited and inversely correlated to fuel consumption (P = −0.763) but, actually, strongly related to greenhouse gas emissions (P = −0.945). This confirms that a plant that works more regularly achieves high environmental efficiency emitting less greenhouse gases. The correlation between fuel average consumption for CCGT plant (*c*) and the average emissions of greenhouse gases (*d*) is not very meaningful (P = 0.617), because it is strongly conditioned by the continuous and increasingly prolonged suspension of production plants.

4. CONCLUSIONS

Despite the modernization of the national electricity sector, in recent years, the severe economic crisis has had heavy repercussions on productivity, on plant utilization factor and, therefore, on the energy and environmental efficiency of the entire thermoelectric sector.

From 2007 to 2016, as a consequence of economic crisis and energy demand, there has been a drastic reduction of annual operating hours (from 4,587 to 1,988 h/years) and electricity production of CCGT power stations (more than 50%, from 85.1 to 39.5 TWh_e). This situation has influenced the operation data and the indicators included in the EMAS Environmental Statements of the plants examined, determining a significant reduction of efficiency. As a consequence, the total consumption of fossil fuels and the overall emissions have also greatly decreased in relation to the less operating time of the CCGT power stations, but, in relation to the electricity produced, the consumption of natural gas and the emissions of greenhouse gases have drastically increased.

The plants that suffered the most pronounced reduction of electricity generations have been small-sized and the large-sized ones, whose production has almost halved, over the decade. The medium-sized plants, more than the other two categories, have better absorbed the shock of the economic crisis and the consequent reduction of national electricity demand. It is conceivable that these plants are, among all the others, the most cost-effective even during under-used facilities situations, owing to their more flexible productions that adapt their processes to the demand variations better and faster than others.

Larger plants have a 10-year average greenhouse gas emission index that is much higher than the others, due to their lower operation rate and to their continuous on/off cycles. In fact, medium-sized plants have, on average, emitted lower quantities of greenhouse gases, due to their longer operating processes and less discontinuous generation cycles. This is evident because they have the best annual operating percentage (38%).

The variations of electricity production from CCGT plants are strongly, and inversely, related to the corresponding variations of electricity production from renewables because both these different sources are in direct competition to satisfy the same daily load peaks of electricity demand. All that clearly suggests that the 10-year reduction of CCGT production took place mainly due, in order of decreasing importance, to: (1) The increase of the production share from renewables; (2) the contraction of national electricity demand and (3) to the decrease of GDP.

4.1. Summary Points

1. In Italy, and in the rest of world, the use of fossil fuels, for electricity production, covers most of the domestic power generation and energy demand.
2. CCGT power systems, which use natural gas as fuel, are considered the best thermoelectric technology available, owing to their high energy efficiency and reduced environmental impact.
3. The indicators of EMAS Environmental Statements are fundamental for a better management of those resource-intensive industrial sectors with significant environmental implications, such as electricity generation ones.
4. This research has been conducted with the aim to carry out a ten-year survey on the situation and trends of few core energy and environmental EMAS indicators of a very representative sample of Italian CCGT power plants, in order to investigate their benchmarking performances.
5. Until now, no scientific publication has yet been issued to investigate these topics.
6. Despite the modernization of the national electricity sector, in recent years, the severe economic crisis has had heavy repercussions on productivity, on plant utilization factor and, therefore, on the energy and environmental efficiency of the entire thermoelectric sector.
7. From 2007 to 2016, as a consequence of economic crisis and energy demand, there has been a drastic reduction of annual operating hours (from 4,587 to 1,988 h/years) and electricity production of CCGT power stations (more than 50%, from 85.1 to 39.5 TWh_e).
8. As a consequence, the total consumption of fossil fuels and the overall emissions have also greatly decreased in relation to the less operating time of the CCGT power stations, but, in relation to the electricity produced, the consumption of natural gas and the emissions of greenhouse gases have drastically increased.
9. The plants that suffered the most pronounced reduction of electricity generations have been small-sized and the large-sized ones, whose production has almost halved, over the decade.
10. Larger plants have a ten-year average greenhouse gas emission index that is much higher than the others, due to their lower operation rate and to their continuous on/off cycles.
11. Medium-sized plants are the most efficient and have, on average, emitted lower quantities of greenhouse gases.
12. The variations of electricity production from CCGT plants are strongly, and inversely, related to the corresponding variations of electricity production from renewables.

4.2. Future Issues

- What is the situation of the CCGT plants of the other European countries?
- How have the electricity production costs of the CCGT plants changed?
- Does renewable energy competition only affect production from CCGT plants?
- In situations of contraction in electricity demand, the only effective measure is to close the most efficient thermoelectric plants?

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