Modelling, Measurement and Control B
Vol. 87, No. 3, September, 2018, pp. 167-171
Journal homepage: http://iieta.org/Journals/MMC/MMC_B

A techno-economic and environmental analysis for carbon capture and storage in Italian power plants

Alberto Fichera, Rosaria Volpe*, Vittoria O. Utili

Dipartimento di Ingegneria Elettrica, Elettronica ed Informatica, viale Andrea Doria 6, Catania 95125, Italy

Corresponding Author Email: rvolpe@dii.unict.it

https://doi.org/10.18280/mmc_b.870308

Received: 26 April 2018
Accepted: 21 May 2018

Keywords:
carbon capture and storage, LCOE (Levelised Cost of Electricity), plant-level approach

ABSTRACT

Coal and natural gas are the most used fuels for the production of electricity; unfortunately, their use pollutes the atmosphere and directly affects the global warming. In this context, Carbon Capture and Storage (CCS) technologies are acknowledged as promising solution in tackling the global warming. To evaluate the convenience of such a solution, the scientific community agree on the need to study both the economic advantages of carbon capture as well as its environmental impact. With reference to the estimation of the cost of CCS in power plants, the most frequently applied method is the so-called plant-level approach. This method compares the costs of electricity for a power plant with and without carbon capture. The environmental impact of CCS, instead, is determined through the calculation of the tons of CO_2 avoided. In accordance with this methodological outline, this paper applies the plant-level approach to study the techno-economic and environmental convenience of installing a CCS system within a CCGT (Combined Cycle Gas Turbine) power plant in Italy, for which operating scenarios are presented and discussed.

1. INTRODUCTION

Anthropogenic greenhouse gas emissions have increased significantly in the last decades and represent a serious concern for the world. Emissions are responsible for the global warming, raising the temperature of the Earth's atmosphere. The AR5, the Fifth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change), states these evidences. In addition, a particular attention has been devoted to the need to mitigate the emissions in order to avoid long-lasting changes in the overall climate system [1-2].

The intense use of fossil fuels for the electricity generation strengthens the impact of the problem. A viable way to reduce the emissions from the power generation sector, and industrial sectors as well, lies in the CCS technology. Carbon Capture and Storage (CCS) includes all technologies enabling the separation of CO_2 from energy-related sources, its transport (via ships or ad hoc constructed pipelines) and its storage in depleted oil and gas fields or in deep saline formations.

Despite the scientific community have recognized the critical role of CCS in mitigating carbon emissions, CCS has not received significant attention from policy-makers and, in addition, its public acceptance is a complex task.

To this scenario, economic uncertainties, proper national regulations and lack of financial supports restrain further developments in this direction.

Currently, around the world, there are some active CCS and several pilot projects at industrial level [3]. However, there are no large-scale capture technologies application in power plant and, particularly in the Italian context, the techno-economic assessment of CCS, and the consequent environmental impact, is studied by means of analytical methods. In the following, a brief list of the scientific contribution is discussed.

The costs of carbon capture and storage are discussed in literature either by focusing on a specific power generation technology or by comparing different technologies. The work of Rubin and Zhai [4] belongs to the first group and examines the cost of CO_2 capture ad storage for NGCC (Natural Gas Combined Cycle) power plants with an amine-based post-combustion CCS system. Mathieu and Bolland [5] also study the NGCC power plants but in terms of competitiveness of the different capture technologies. USCPC (Ultra Supercritical Pulverized Coal Combustion) with and without CCS is studied in Viskovic et al. [6] as an investment possibility in Croatia.

As regard to the comparison among different power generation technologies, the work of Li et al. [7] evaluates the techno-economic performance of a substitute/synthetic natural gas (SNG) and a power cogeneration technology with CCS. Siefert et al. [8] conduct an exergy and economic analysis of an advanced integrated gasification combined cycle (IGCC) with H_2 and O_2 membrane separation and of an integrated gasification fuel cell cycle with a catalytic gasifier and a pressurized solid oxide fuel cell (IGFC).

Other authors evaluate the potential benefit arising from the integration of renewable sources. In this direction, Cau et al. [9] consider the integration of concentrating solar collectors to USC power plants. On the same issue, Al-Qayim et al. [10] carry out a techno-economic assessment of biomass and coal with different capture technologies for pulverized combustion in the United Kingdom. The potential of renewables is also studied in the work of van den Broek et al. [11]. The study evaluates the costs of intermittent renewable energy systems and compares them to those of NGCC with CCS. Finally, wind power plants in comparison with gas-fired power plants are the subject of the analysis conducted by Heuberger et al. [12].

With respect to the papers focusing on Italian case study, Pettinau et al. [13] present a techno-economic comparison between ultra-supercritical pulverized coal combustion (USC) and an IGCC at different capture configurations. The reference location for the plant configurations is the Sulcis basin, in Sardinia. In a subsequent work, the authors [14] compare USC, OCC (Oxy-Coal Combustion) and IGCC in their conventional configuration without CCS and with CCS to determine the most convenient solution among them.

The cited literature is without doubt exhaustive and full of details about the techno-economic assessment of power generation technologies with and without CCS; in addition, proper studies have highlighted the differences among capture technologies as well as the role of renewable energy. However, to our knowledge, few papers focus on the specificity of the Italian power generation context. On the contrary, the sole studied case study is the Sulcis basin. Therefore, this work aims to give a contribution in this direction and proposes a techno-economic analysis of typical Italian power plants with and without CCS. The rest of the paper is organized as follows: Section 2 gives a brief overview of the Italian electricity sector. Section 3 introduces the method used for the assessment of the techno-economic analysis. Results are discussed in Section 4 and conclusions are provided in Section 5.

2. THE ITALIAN CONTEXT: A BRIEF OVERVIEW

The electricity generation mix is largely represented by natural gas, coal and oil. Oil use for the electricity generation decreased significantly in the mid-1990s in favour of the natural gas that is now the largest fuel used in the electricity sector. The majority of natural gas and coal relies on imports; indeed, the only coal source in Italy is the Sulcis Iglesiente bacin, in southwest Sardinia [15].

In 2016, the total electricity generation reached 284.1 TWh with a total installed generating capacity of 117.7 GW. In that year, natural gas, coal and oil represented the 61% of total generation, in detail 42% natural gas, 15% coal and 4% oil. The remainder 39% is constituted of renewables sources, i.e. 15% hydro, 8% biofuels and waste, 8% solar, 6% wind and 2% geothermal [16]. A graphical representation of these percentages is reported in Figure 1.

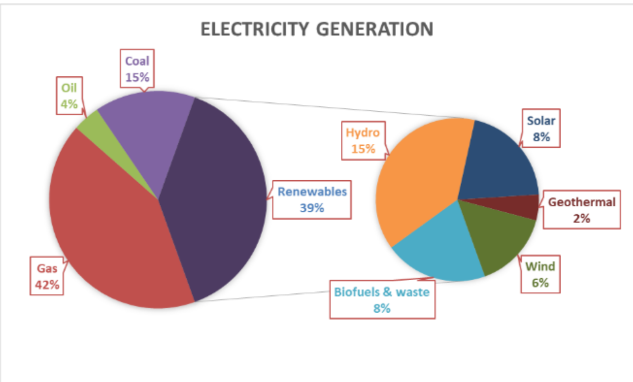

Figure 1. Electricity generation by source (Italy, 2016)

As regard to the electricity generating technologies, Figure 2 gives an overview of the natural gas-fired and coal-fired generation in Italy. Combined-Cycle Gas Turbine (CCGT) technologies account for the 78% of the total plants, followed by the Ultra Super Critical (USC) plants (17%) and the Integrated Gasification Combined-Cycle (IGCC), with the 5% [17-19]. However, no IGCC plants in operation in Italy produce electricity for the national market. Rather they are mainly at the service of refineries and use TAR as fuel, otherwise difficult to dispose of.

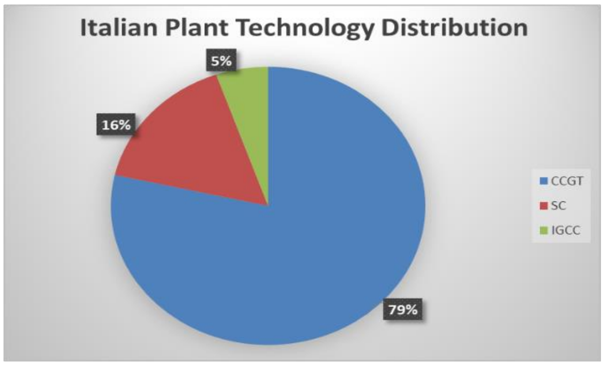

Figure 2. Electricity generating technologies in Italy

Among the CCGT technology, the most widespread size of power plants varies between 650 and 750 MW [17 – 19].

As widely recognized, the role of the electricity sector in reaching the climate goals for 2050 is crucial. In this direction, it has been estimated that CCS could significantly reduce carbon emissions deriving from the use of fossil fuels. To raise the awareness on the importance of CCS, the European Commission has regulated the process to be followed by the Member States in the Directive 2009/31/EC and the Italian transposition of the Directive has been implemented in the Legislative Decree 162/2011. In addition, to both increase the competitiveness and improve the flexibility of its energy sector, the Italian government has approved the National Energy Strategy (NES) [20]. This document paves the way for the definition of a common and viable energy strategy and includes, among its key goals, the reduction of the energy consumptions along with the decarbonisation of the energy sector by means of the CCS.

In 2011, in response to this regulatory regime, Italy implemented a post-combustion CCS pilot project at the Federico II coal-fired power plant in Brindisi. The project aimed at capturing 8000 tons of CO_2 per year [21]. However, the pilot project has been stopped and the dismantling of the power plant has been commissioned before 2025 [22]. In 2014, a further CCS project has been designed for the oil-plant in Porto Tolle. The initial aim was to convert the plant into a coal-fired plant equipped with CCS technology. Unfortunately, delays and red tape contributed to the failure of the project [21]. The only Italian initiative focusing on the implementation of CCS technologies is the “Integrated Sulcis Project” in the Sardinian Sulcis area. The project is, at this time, in a study phase after which a new coal plant with CCS is planned to be build.

Both the decision to dismantle Federico II and the cancellation of the project in Porto Tolle imply that Italy has any CCS-related development to pursue at this moment. Therefore, to determine to what extent CCS may contribute to the abatement of the carbon emissions deriving from the Italian electricity sector, the only viable way is so far analytical.

To the purpose, the key goal of this paper is to compare two different plant configurations based on CCGT, the most widespread electricity generating technology in Italy. Therefore, a traditional CCGT plant (where CO_2 is released in the atmosphere) and a CCGT equipped with a post-combustion CCS system are compared from the techno-economic and environmental point of view.

3. MATERIALS AND METHODS

The most frequently applied method for the techno-economic analysis of power plants is the so-called plant-level approach. It consists in comparing different plant configuration with and without CCS from the economic viewpoint by introducing a purpose-built indicator, called LCOE (Levelized Cost of Electricity). Actually, the method consists in comparing the cost of electricity for a plant without CCS (and called *reference plant*) and a plant with CCS (also called *CCS plant*). Two basic assumptions are based on this approach [23]; they are briefly summarized in the following:

- the reference plant and the plant with CCS have the same power generation technology and similar power size;
- plants are new (no retrofitting allowed).

These assumptions have practical implications. The first assumption ensures the effectiveness of the comparison between the reference plant and the CCS plant. Actually, different technologies are not comparable due to the different fuel used, the different costs and emissions. Similar considerations yield for the size of the power plant. The second assumption derives from the fact that existing power plants have gained a market competitiveness due to their low generation costs that would alter the results in terms of the cost of electricity. In addition, the retrofit of an existing plant would cause an efficiency penalty that is difficult to consider within the calculation.

As stated, the plant-level approach compares the two plant configurations on the ground of the LCOE. This indicator expresses the average revenue per unit of electricity production required to cover all investment and operating costs. Accordingly, it is calculated by the equation:

$$LCOE = \frac{TCR*FCF + FOM}{NAG*NPO} + VOM + HR*FC \qquad (1)$$

In Eq.(1), the LCOE includes three main cost items, i.e. the capital investment costs, the operation and maintenance costs and the fuel costs [24].

The capital investment costs are expressed by the TCR, the Total Capital Requirement that represents the initial investment of the project. The TCR is annualized by the Fixed Charge Factor (FCF) that returns the uniform annual amount of the total capital value. In its definition, the FCF takes the discount rate and the economic life of the plant into account.

The operation and management costs are divided in their fixed and variable components, respectively FOM and VOM. The FOM costs are the annual expenditure of the project for O&M costs that remain relatively constant, such as operating and maintenance labor, administrative labor, salaries, taxes and insurance. The VOM costs, instead, refer to the costs that strictly depend on the operating hours of the plant, such as consumables (water, chemicals, etc.), emission taxes, waste disposal.

The annualized capital cost, given by the product TCR*FCF and the fixed operation and management costs, FOM, are divided by the sum of the net power output of the plant (NPO) and the net annual generation (NAG).

Finally, the last term represents the fuel costs (FC), i.e. the total expenditure for fuel over the assumed lifetime of the plant. The FC is multiplied by the heat rate (HR) of the power plant, a unit conversion efficiency measure.

Another frequently calculated indicator when dealing with the analysis of CCS technologies is the cost of the CO_2 avoided, MC, that is the cost of CO_2 avoided, MC, that is the cost of reducing carbon emissions to the atmosphere by one unit of mass while still producing one MWh of electricity [4]. The MC, acronym for Mitigation Cost, evaluates the tons of CO_2 avoided due to a CCS system and represents a useful benchmark to determine to what extent th e CCS is attractive for the considered plant [24]. Its formulation is defined as:

$$MC = \frac{LCOE_{CCS} - LCOE_{ref}}{ER_{ref} - ER_{ccs}} \qquad (2)$$

The terms $LCOE_{ccs}$ and $LCOE_{ref}$ are the levelized cost of electricity for plants with and without CCS, respectively; the terms at the denominator, ER, refer to the emission rates, expressed as the tons of CO_2 per MWh released to the atmosphere and the subscripts distinguish the two cases of a plant with and without CCS.

4. GENERAL ASSUMPTIONS AND RESULTS

The main problem when conducting a techno-economic analysis of CCS within power plants regards the uncertainness about costs. Actually, not any CCS installation has been implemented on Italian power plants and, consequently, data have been collected and elaborated from authoritative sources, such as the IEA (International Energy Agency), the ENEA (the Italian national agency on technologies, energy and sustainable economic growth) and the GCCSI (Global CCS Institute). Other assumptions derive from the scientific literature, properly cited within this work.

The first peculiar assumption of this analysis concerns the chosen plant technology and its net power output. With respect to the plant technology, a CCGT power plant has been analysed. As also discussed in the previous paragraph, CCGT represents the most widespread plant technology in the Italian territory. A 700 MW size power plant has been selected for the simulation, in accordance with the typical size distribution of CCGT in Italy. These and the other assumptions are summarized in Table 1.

Table 1. Assumptions used in this study

Parameter	Value	Source
Plant technology	CCGT	-
Plant size [MW]	700	-
Capacity factor	85%	[7]
Lifetime [y]	20	[7]
CCS technology	Post-combustion	

The capacity factor indicates the maximum annual availability for the plant. It is quantified on the ground of the generation technology considered in the study. For instance, in the case of dispatchable generation (as in the case of coal, nuclear and gas-fired plants), the standard capacity factor of 85% is assumed to be valid [25]. The capacity factor is used to calculate the NAG, i.e. the net annual generation. Multiplying the capacity factor by the total annual generation hours (24 h/d *365 d/y) yields the NAG that are the number of hours in a year that the plant is assumed to run. The lifetime indicates the expected years that the plant will operate.

As regard to the cost assumptions for the calculation of the LCOE, a more detailed overview is offered in Table 2. In addition to the values of the data used in this study, Table 2 lists also the sources from which the data were recorded and elaborated. In particular, data are displayed within the Table to highlight the comparison between the LCOE of a CCGT power plant without CCS and with CCS. The results of both LCOE are shown in the last row of Table 2.

Table 2. LCOE calculation

	CCGT w/o CCS	CCGT with CCS	Source
TCR [M€]	593,32	1665,71	[6]
FCF [%]	0.11	0.11	[4]
FOM [M€/y]	188.25	249.7	[3]
NAG [h]	7446	7446	[6]
NPO [MW]	700	700	[9]
VOM [€/MWh]	1.05	3.56	[3]
HR [MJ/MWh]	6.652	7.945	[3]
FC [€/MJ]	7	7	[5]
LCOE €/MWh]	97.10	133.35	

As expected, the LCOE for the configuration of CCGT with CCS is significantly higher with respect to the configuration without CCS, due to the higher costs.

Figures 3 and 4 show the impact of the three main cost components, i.e. capital costs, O&M costs and fuel costs, on the LCOE for the CCGT plant without CCS and for the CCGT plant with CCS, respectively. As can be observed, and independently of the CCS technology, the most relevant cost component is the fuel expenditure over the whole lifetime of the plant, followed by the O&M costs and finally by the capital costs. Regarding the comparison between CCGT with and without CCS, the configuration with the CCS is more impacting on the LCOE.

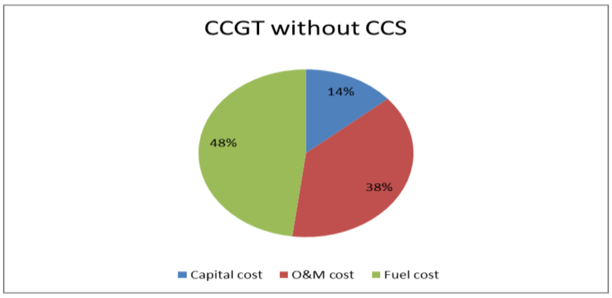

Figure 3. Cost components impact; case CCGT w/o CCS

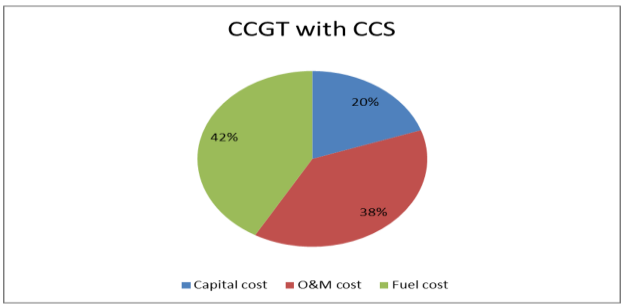

Figure 4. Cost components impact; case CCGT + CCS

The MC corresponds to the carbon tax for the CCGT without CCS (i.e. the reference plant) equals that of the CCGT with CCS. Therefore, CCS within a CCGT power plant may be considered as an attractive solution if the carbon prices are near the value of 115.62 €/tCO_2.

5. CONCLUSIONS

This paper carried out a techno-economic analysis of two different plant configurations in Italy in order to obtain insights into the feasibility of building a new power plant equipped with CCS systems. The plant technology and its power size were chosen with respect to the actual Italian generating technology distribution; thus leading to the study of a 700 MW CCGT power plant with and without CCS. The method used to compare the two configurations was the plant-level approach, for which the LCOE and CCA were calculated and discussed. All basic assumptions and costs derive from authoritative sources and authors, with a special focus on studies reporting Italian actual data.

The results show a significantly higher LCOE for the configuration of CCGT with CCS. However, the cost of CO_2 avoided reveals that the choice to consider a CCGT with CCS may be considered advantageous if the carbon price equals the value of 115.62 €/tCO_2.

In forthcoming research, more complex configurations as well as retrofitting options for the existing Italian power plants will be studied.

REFERENCES

[1] IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151.

[2] Zhang Y, Wang D, Yang J, Adu E, Shen Q, Tian L, Wu L, Shi B. (2017). Correlative comparison of gas CO_2 pipeline transportation and natural gas pipeline transportation. Modelling, Measurement and Control 86(1): 63-75. https://dx.doi.org/10.18280/mmc_b.860105

[3] Global CCS Institute 2014, The Global Status of CCS: 2014, Melbourne, Australia.

[4] Rubin ES, Zhai H. (2012). The cost of carbon capture and storage for natural gas combined cycle power plants. Environmental Science and Technology 46: 3076-3084. https://dx.doi.org/10.1021/es204514ff

[5] Mathieu P, Bolland O. (2013). Comparison of costs for natural gas power generation with CO_2 capture. Energy 37: 2406-2419. https://dx.doi.org/10.1016/j.egypro.2013.06.122

[6] Viskovic A, Franki V, Valentic V. (2014). CCS (carbon capture and storage) investment possibility in South East Europe: A case study for Croatia. Energy 70: 325-337. https://dx.doi.org/10.1016/j.energy.2014.04.007

[7] Li S, Jin H, Gao L, Zhang X, Ji X. (2014). Techno-economic performance and cost reduction potential for the substitute/synthetic natural gas and power cogeneration plant with CO_2 capture. Energy Conversion and Management 85: 875-887. https://dx.doi.org/10.1016/j.econman.2013.12.071

[8] Siefert N, Litster S. (2013). Exergy and economic analyses of advanced IGCC-CCS and IGFC-CCS power plants. Applied Energy 1107: 315-328. http://dx.doi.org/10.1016/j.apenergy.2013.02.006

[9] Cau G, Cocco D, Tola V. (2014). Performance assessment of USC power plants integrated with CCS and concentrating solar collectors. Energy Conversion

and Management 88: 973-984. https://dx.doi.org/10.1016/j.enconman.2014.09.040
[10] Al-Qayim K, Nimmo W, Pourkashanian M. (2015). Comparative techno-economic assessment of biomass and coal with CCS technologies in a pulverized combustion power plant in the United Kingdom. International Journal of Greenhouse Gas Control 43: 82-92. https://dx.doi.org/10.1016/j.ijggc.2015.10.013
[11] van den Broek M, Berghout N, Rubin ES. (2015). The potential of renewables versus natural gas with CO_2 capture and storage for power generation under CO_2 constraints. Renewable and Sustainable Energy Reviews 49: 1296-1322. https://dx.doi.org/10.1016/j.rser.2015.04.089
[12] Heuberger CF, Staffell I, Shah N, Mac Dowell N. (2017). What is the value of CCS in the future energy system? Energy Procedia 114: 7564-7572. https://dx.doi.org/10.1016/j.egypro.2017.03.1888
[13] Pettinau A, Ferrara F, Amorino C. (2013). Combustion vs. gasification for a demonstration CCS (carbon capture and storage) project in Italy: A techno-economic analysis. Energy 50: 160-169. https://dx.doi.org/10.1016/j.energy.2012.12.012
[14] Pettinau A, Ferrara F, Tola V, Cau G. (2017). Techno-economic comparison between different technologies for CO_2-free power generation from coal. Applied Energy 193: 426-439. https://dx.doi.org/10.1016/j.apenergy.2017.02.056
[15] Mills S. (2015). Prospects for coal and clean coal technologies in Italy. IEA Clean Coal Center, United Kingdom, Report CCC/254.
[16] IEA, International Energy Agency. (2016). Italy – Energy System Overview. Available at: https://www.iea.org/media/countries/Italy.pdf.
[17] GSE, Gestore Servizi Energetici. (2018). Statistiche, dati e scenari database. Available at: https://www.gse.it/Dati-e-Scenari_site/statistiche_site (in Italian).
[18] Terna SPA. (2017). Impianti di produzione essenziali per la sicurezza del Sistema elettrico ai sensi dell'articolo 63, comma 63.1, dell'Allegato A alla delibera dell'AEEGSI n. 111/06 – Elenco valido per l'anno 2017. Allegato A27. Available at https://download.terna.it/terna/0000/0848/17.PDF (in Italian).
[19] ARERA, Autorità di Regolazione per Energia Reti e Ambiente. (2017). Produttori, impianti e generazione per fonte, Indagine annuale sui settori regolati. Relazione annuale giugno 2017, available at http://www.arera.it/it/dati/eemprod2.5.htm (in Italian).
[20] Ministero dello Sviluppo Economico. (2017). SEN 2017 – Strategia energetica nazionale. Available at: www.sviluppoeconomico-gov.it/index.php/it/energia/strategia-energetica-nazionale (in Italian).
[21] Energy Policies of IEA Countries, Italy, 2 Review. IEA International Energy Agency, Secure Sustainable Together, available at: http://www.iea.org/publications/freepublications/publication/EnergiePolicesofIEACountriesItaly2016Review.pdf.
[22] Carbon Capture and Sequestration Technologies at MIT. (2016). Brindisi Fact Sheet: Carbon Dioxide Capture and Storage Project. MIT, Massachusetts Institute of Technology
[23] Tzimas E, Peteves S. (2002). Controlling carbon emissions: the option of carbon sequestration. European Commission, Joint Research Center, Petten, The Netherlands, Report EUR 20752 EN.
[24] Rubin ES, Short C, Booras G, Davison J, Ekstrom C, Matuszewski M, McCoy S. (2013). A proposed methodology for CO_2 capture and storage cost estimates. International Journal of Greenhouse Gas Control 17: 488-503. https://dx.doi.org/10.1016/j.ijggc.2013.06.004
[25] IEA, International Energy Agency. (2015). Projected Costs of Generating Electricity. NEA Nuclear Energy Agency.

NOMENCLATURE

CCGT	Combined-Cycle Gas Turbine
CCS	Carbon Capture and Storage
ERccs	Emission Rate for the plant with CCS
ERref	Emission Rate for the plant without CCS
FC	Fuel Cost
FCF	Fixed Capital Factor
FOM	Fixed O%M costs
HR	Heat Rate
IGCC	Integrated Gasification Combined Cycle
LCOE	Levelized Cost Of Electricity
LCOEccs	Levelized Cost Of Electricity for the plant with CCS
LCOEref	Levelized Cost Of Electricity for the plant without CCS
MC	Mitigation Cost
NAG	Net Annual Generation
NES	National Energy Strategy
NPO	Net Power Output of the plant
TRC	Total Capital Requirement
VOM	Variable O&M costs
USC	Ultra Super Critical