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Review

The CO_2 economy: Review of CO_2 capture and reuse technologies

Efthymia Ioanna Koytsoumpa[a,b,*], Christian Bergins[a], Emmanouil Kakaras[a,b]

[a] Mitsubishi Hitachi Power Systems Europe GmbH, Schifferstraße 80, 47059 Duisburg, Germany
[b] National Technical University of Athens, Laboratory of Steam Boilers and Thermal Plants, 9 Heroon Polytechniou, Zografos 15780, Athens, Greece

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ABSTRACT

The continuously increasing share of Renewable Energy Sources (RES) and EU targets for CO_2 reduction and energy efficiency necessitate significant changes both on technical and regulatory level. Environmental challenges of CO_2 emissions are assessed in a review of CO_2 capture and utilisation technologies, offering new opportunities in CO_2 economy. Commercial applications in the thermal power and industrial sector for pre and post combustion capture as well as the potential of direct air CO_2 capture are reviewed. The potential of Carbon Capture and Utilisation (CCU) is assessed focusing on the use of CO_2 for fuel as well as for combined heat and power production. Combining CCU with energy storage as an evolutionary measure for balancing RES with thermal power under the power to fuel concept presents high market potentials for fuel and chemical production. Moreover, the recent progress in supercritical CO_2 cycles for combined heat and power production is reported.

1. Introduction

The European Union (EU) energy strategy for 2030 and 2050 sets specific targets for the transition of the current European energy system towards a low carbon energy system with decreased GreenHouse Gas (GHG) emissions, increased energy efficiency and increased share of Renewable Energy Sources (RES). Especially for 2030 a 40% reduction in carbon emissions and at least a 27% EU-wide share for renewables in primary energy consumption is foreseen. The overall electricity generation mix in EU has been following a decreasing trend over the last few years, as a result of dwindling fossil fuel generation (mainly coal and gas), with stagnating shares of nuclear and hydro, and a continuously increasing share of renewables. Different velocities are observed in energy transition of EU Member states with Germany and Austria to adopt more ambitious targets towards the increase of installed capacity and production of RES, while other straggle to meet EU targets. After the 21st United Nations Climate Change Conference in Paris in 2015, COP21 agreement sets a new benchmark − limit the rise in global average temperature to well below 2 °C − in order to mobilise international political response and measures to climate change. It vindicates the EU's early efforts and associated legislation to reduce carbon emissions, and the thermal power industry is ready to tackle the associated challenges. The old fleet of thermal power plants is not optimised for flexible operation. The existing plants are operated now at very low part-load efficiencies, and therefore both emissions and resource consumption are high. So the fleet is not able to contribute to policy goals. Simultaneously, the increasing of RES cannot be continued without safety measures and careful considerations. Decreasing fossil fuel- fired power plant capacity without any countermeasures endangers the security of energy supply, which is challenging in an industry-based society like EU [1,2]. An insufficient network infrastructure represents an important barrier for RES, increasing

Abbreviations: BOF, basic oxygen furnace; BTX, benzene, toluene, xylene; CAES, compressed air energy storage; CCS, carbon capture and storage; CCU, carbon capture and utilisation; CHP, combined heat and power; DAC, direct air capture; DEA, diethanolamine; DEPG, dimethyl ether of polyethylene glycol; DGA, aminoethoxyethanol; DME, dimethyl-ether; DOE, department of energy, US; DPA, diisopropanolamine; EJ, exajoules; EOR, enhanced oil recovery; EPPSA, European power plant suppliers association; ESA, electrical swing adsorption; ESI, emirates steel industries; EU, European union; FQD, fuel quality directive; GHG, greenhouse gas; GJ, gigajoules; Gt/y, gigatonnes per year; HECLOT, high-efficiency calcium looping technology; HTHP, high temperature heat pump; ICEs, internal combustion engines; IGCC, integrated gasification combined cycle; kg, kilogramms; LAES, liquid air energy storag e; LHV, lower heating value; M100, pure methanol fuel; M15, 15% blend of methanol in gasoline fuel; M50, 50% blend of methanol in gasoline fuel; M95, 95% blend of methanol fuel; MDEA, Methyldiethanolamine; MEA, monoethanolamine; MeOH, methanol; MHI, mitsubishi heavy industries; MJ, megajoules; MTBE, methyl *tert*-butyl ether; MTG, methanol-to-gasoline process; Mtpa, million tonnes per annum; MWe, megawatt electric; MWhe, megawatthours electric; MWhth, megawatthours thermal; MWth, megawatt thermal; NMP, *N*-methyl-2-pyrrolidone; OECD, organisation for economic co-operation and development; OMEs, oxy-methylene ethers; PC, propylene carbonate; PCC, post-combustion capture; PPI, pulp and paper industry; ppm, parts per million; PSA, pressure swing adsorption; PtM, power to methanol; RED, renewable energy directive; RES, renewable energy sources; SMP, system's market price; SNG, substitute natural gas; SOFC, solid oxide fuel-cell; TEA, triethanolamine; TOU, time-of-use pricing; TSA, temperature swing adsorption; TTGR-BF, top gas recycle blast furnace; TVS, temperature vacuum swing; US, United States; vol%, volume percentage; VPSA, vacuum pressure swing adsorption; VSA, vacuum swing adsorption

* Corresponding author at: Mitsubishi Hitachi Power Systems Europe GmbH, Schifferstraße 80, 47059 Duisburg, Germany.
E-mail address: e_koytsoumpa@eu.mhps.com (E.I. Koytsoumpa).

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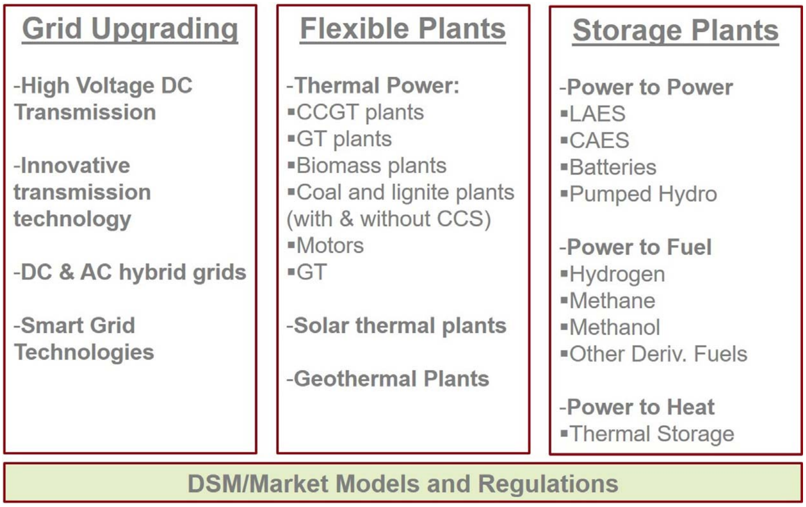

Fig. 1. Technology portfolio in high RES systems.

penetration leading to increased levels of curtailment or requiring additional back up capacity, which can be provided by thermal power and combinations of thermal power and energy storage. On the other hand, the coupling of electricity markets leads to a better utilization of the energy sources and lower electricity prices, the System's Market Price (SMP) reduction is a fact with profound examples that of Germany and Spain due to the "merit order" effect. All effects of energy policy, including rising electricity prices in the consumers' side, might lead to awakening of the European economies if no prompt political counter measures are taken either by Member States or, preferably, on the EU-level. The increasing share of intermittent RES comes with technical and market challenges, which need to be faced with flexible thermal plants, improved RES-technology and reactive power, a Pan-European overlay grid, transmission technologies with improved grid monitoring, control and effective energy storage. Although the coupling of electricity markets in Europe leads to a better utilization of the energy sources and lower electricity prices, technical challenges need to be faced. The technology portfolio for high RES Systems is depicted in Fig. 1.

The main question for the future development of power industry and electricity markets is the security of supply, the energy efficiency and the decarbonisation. In the decarbonisation efforts and energy efficiency, the EU Commission has already set up a roadmap towards 2030 and 2050. The thermal power generation sector has already performed considerable steps towards reduction of carbon footprint and increase of energy conversion efficiency and is expected to have a considerable share in the European generation mix until 2030 [1,2]. The security of supply and the market model are still under investigation. Two aspects can be highlighted here. First, taxes and policy costs make electricity artificially expensive to end users, thus hampering decarbonisation not only via shifting the costs to end users but also by hindering market incentives for the necessary investments either as capacity investments or as the deployment of storage technologies which support both energy efficiency and avoidance of energy curtailment. Secondly, today's demand side management should be enriched for the future high RES system. Additional measures are considered such as integration of wholesale markets with day-ahead market coupling and cross-border intraday and balancing electricity markets. These measures together with grid upgrading, which requires high investments (transmission lines), cannot currently assure and guarantee a successful and advanced market design due to the complexity of the algorithm with the combination of centralised, decentralised and smart grid systems. Although price incentives (time-of-use pricing −TOU) are provided to consumers for the reduction of their energy self-consumption and/or moderation of their peak demand and shift of it over time, clearly indicates that shifting the choice to single consumers provides no answer to the security of supply. From the technical point of view, the existence of dispatchable flexible and back-up capacity in combination with energy storage technologies is the future technology responses to secure an efficient energy transition. In this context, dispatchable and flexible thermal power will provide primarily back-up to RES and will be able to simultaneously provide primary and secondary control services, supporting grid stability and also heat to heat grids. Capacity remuneration markets with stand-by thermal power plants and their balancing with a cross-sectorial approach of energy shift to heat grids and storage technologies would allow the development of regional adequacy assessments with cross-border participation.

The need for energy storage has received significant attention with several roadmaps to arise in European level as well as in Japan and China, in California and US [3–7]. Energy storage technologies can be categorized as electric to electric, electric to heat, electric to chemicals as well as according to their installed capacity and time response ranging from seasonal, to day, to hour or minute. Energy storage, when directed to electricity grid, can provide arbitrage services, frequency regulation, load following, voltage support, transmission and distribution services, back up reserve services with basic technologies being represented by pumped hydro, flywheel and compressed air energy storage (CAES) transform, Liquid Air Energy Storage (LAES) and batteries. However, there is also a variety of energy storage technologies acting as energy adsorbents and directing the end product to heat and chemical market. Electric to heat energy storage technologies include thermal and solar thermal storage either in large scale such as combined heat and power plants, small scale decentralized heat applications or LAES technologies for heat recovery and electricity generation in different scales. Electric to chemicals energy storage technologies or power to fuel technologies include power to hydrogen, power to substitute natural gas (SNG), power to methanol as well as many other derivatives directing their end products to chemical market or the global transportation sector. Focusing on power to fuel, any fuel or chemical requiring at least one carbon and one hydrogen molecule enables the combination of energy storage and Carbon Capture and Utilisation (CCU).

The present work assesses the environmental challenges of CO_2 emissions as new business opportunities in a CO_2 trans-sectorial economy. A review of commercial applications in the thermal power sector and industrial sector for pre and post combustion capture, the potential of direct air capture as well as the potential of Carbon Capture and Utilisation (CCU) options are presented. Among those, a special focus on power to fuel technology is given for the conversion of CO_2 to fuels and chemicals, while the use of CO_2 in supercritical cycles for combined heat and power production is reviewed.